The Impact of Dual Energy Saving Technologies on a Frigate's Duties

J E Buckingham* BSc, MSc, CEng, FIMechE

*BMT Ltd, UK

*Corresponding Author. Email: John.Buckingham@uk.bmt.org

Synopsis

There is a fundamental need for naval vessels to address their moral and national responsibilities to the IMO's requirement to reduce carbon intensity by 40% or more by 2030. Existing vessels have limited means to do this without immediate recourse to low carbon fuels, something not feasible for interchangeable operations with allies in a worldwide context. Energy Saving Technologies (EST) with technologies that reduce energy consumption therefore offer a means to reduce the ship's energy efficiency index (EEI).

The adoption of a combination of a wind propulsion device and microbubble drag-reduction on the BMT Venator 110 frigate is explored to identify the benefits at a range of speeds and sea-states. The potential for other propeller benefits in terms of higher efficiency are explored together with the scope for reduced roll and how that may benefit rudder usage and resistance. The likely heel angles achieved with a steady side wind are also considered and their impact on added resistance scoped.

The study identifies the beneficial impact of the EST on the ships fuel consumption for a range of sea states and considers the overall beneficial outcomes when time at different sea states and their mid-range wind conditions are considered.

Keywords: Energy Saving Technologies, Frigate Power & Propulsion

1. Introduction

This paper presents the outputs of a study which explored the benefits of operating with two different types of energy saving technology (EST) on BMT's Venator 110m frigate. Additionally, the paper describes the basic assessment of the impact the wind propulsion device has upon the vessel's roll behaviour due to sideways forces and other effects due to the ship-wind-device interaction.

Whilst there are often studies which address the benefits of a suite of hydro-dynamic advances (Stark, 2022), there have been none identified which address the application of multiple EST to a ship and its operating profile.

The context is that the UK armed forces accounts for 50% of the UK central government's greenhouse gas (GHG) emissions, (MoD, UK, 2021). The IMO has also recently set a minimum 5% target for GHG reductions by 2030, (IMO, 2023).

According to the Intergovernmental Panel on Climate Change, (IPCC, 2022), global emissions need to be cut by 43% by 2030 to stop temperatures rising above 1.5°C above pre-industrial levels, the threshold at which scientists have warned of potentially irreversible changes to the planet and devastating consequences for citizens.

2. Baseline Vessel

The BMT Venator 110m frigate is used as the design basis for these studies, (Kimber, 2008.1) & (Kimber, 2008.2). The exploration of the design option led to the basis-design presented below, (BMT, 2016). The vessel is a good representation of the larger modern, diesel-powered warships used by a range of European navies.

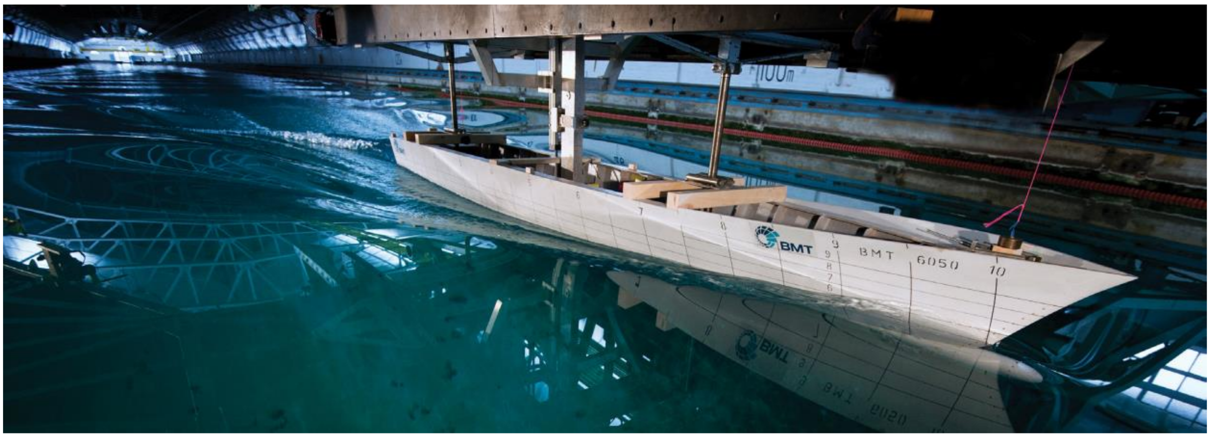

Figure 1. BMT Venator 100m hullform under model testing

3. Study Vessel

The principal particulars of the study vessel are shown in Table 1.

Parameter	Value	Comments
Length overall	117m	
Length waterline	107m	
Draught	4.3m	Standard displacement
Displacement, standard	4,000 tonnes	Nominal
Beam, maximum	18m	
Top speed	> 25 knots	Calm, clean hull
Range	6,000nm at 15 knots	

Table 1. Vessel Principal Particulars

Hullform coefficients and other characteristics relating to the Power and Propulsion (P&P) are as designed by BMT.

The vessel design is aimed at flexibility with a credible mission system fit. The flexibility and potential tailoring options of VENATOR-110 enables the challenges presented by the range of military needs and budgets to be met to fulfil existing and potential future global tasking within a broad range of threat environments.

The main propulsion machinery is shown in Table 2.

Equipment	Make-model	Comments
Main engine	4 x MTU 16V8000M91, each rated at 8,000kW	Temperate conditions
DG Set	4 x MTU 16V2000M41B, engines rated at 930kW.	Temperate conditions
Propeller	3.8m diameter, CPP	Five blades
Ships Electrical load	1,918kWe	Temperate conditions

Table 2. Venator 110 Main Machinery Specification

The machinery is configured in a Combined Diesel And Diesel (CODAD) configuration. The limited engine room space means a hybrid arrangement is not feasible.

Standard specific fuel consumption (Sfc) characteristics as issued by the engine manufacturer have been used. These are subject to a ±5% tolerance iaw ISO standards but the key outputs from this study are the changes to the baseline due to the addition of EST, not the absolute values.

The operating profile as shown in Figure 2 varies with sea state where the upper operating speed may be curtailed by the added resistance due to waves, which was estimated from the IMO method detailed in IMO MEPC/1/Circ. 850.Rev 3 and whose effects are shown in Figure 3.

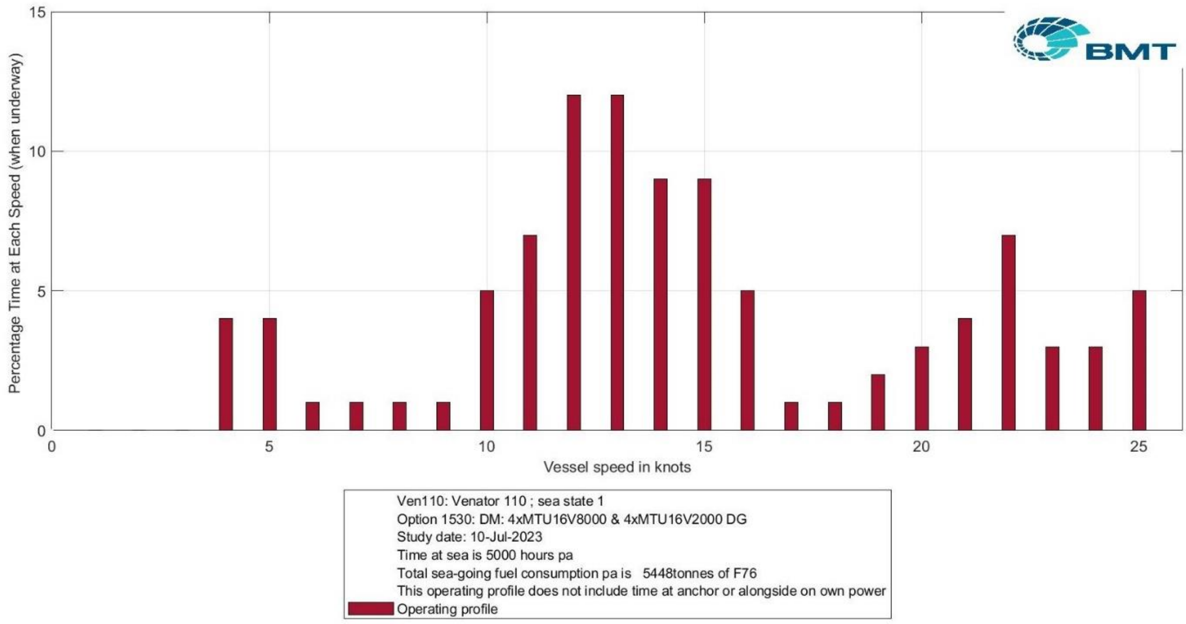

Figure 2. Venator 110 time-speed operating profile

The added resistance in waves is modelled using the IMO method. The impact of this effect is shown in Figure 3.

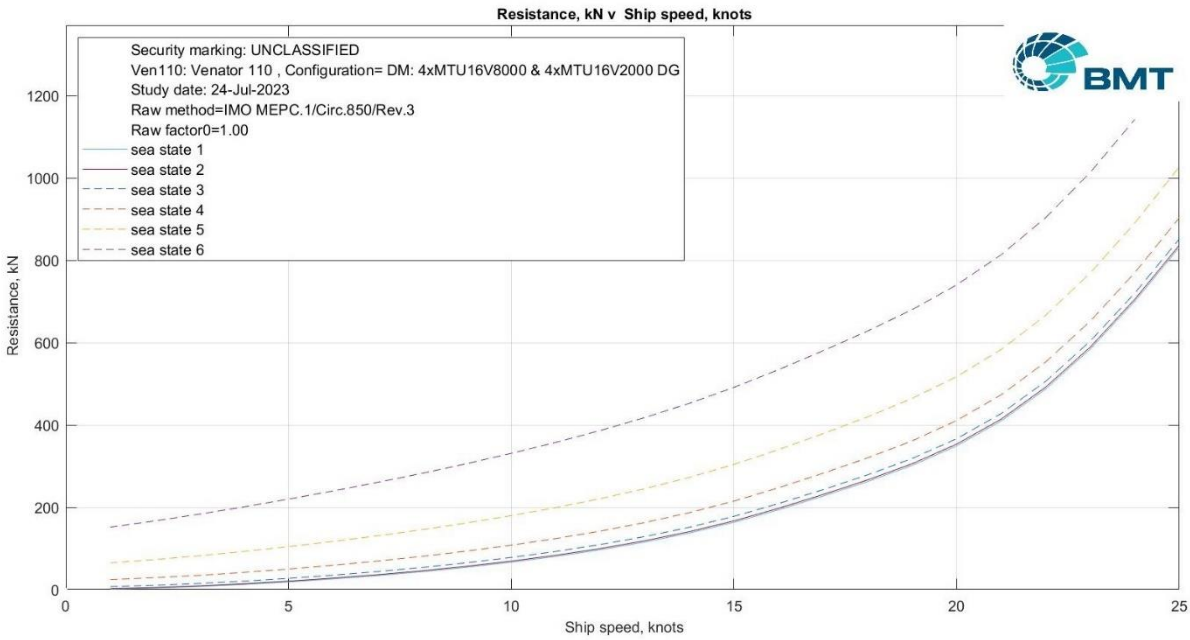

Figure 3. Variation of ship resistance versus speed with sea states 1-6

The ship is assumed to spend 5,000 hours at sea underway per year. Integer ship speeds from 1 to top speed were studied at wind speeds for sea states 1 to 7 in temperate conditions.

There are other assumptions in the definition of the baseline P&P system. However, they are adequate to allow the outputs of an analysis of the EST to be shown.

Figure 4 shows the engine loading across the ship speed range at sea state 1 (SS1).

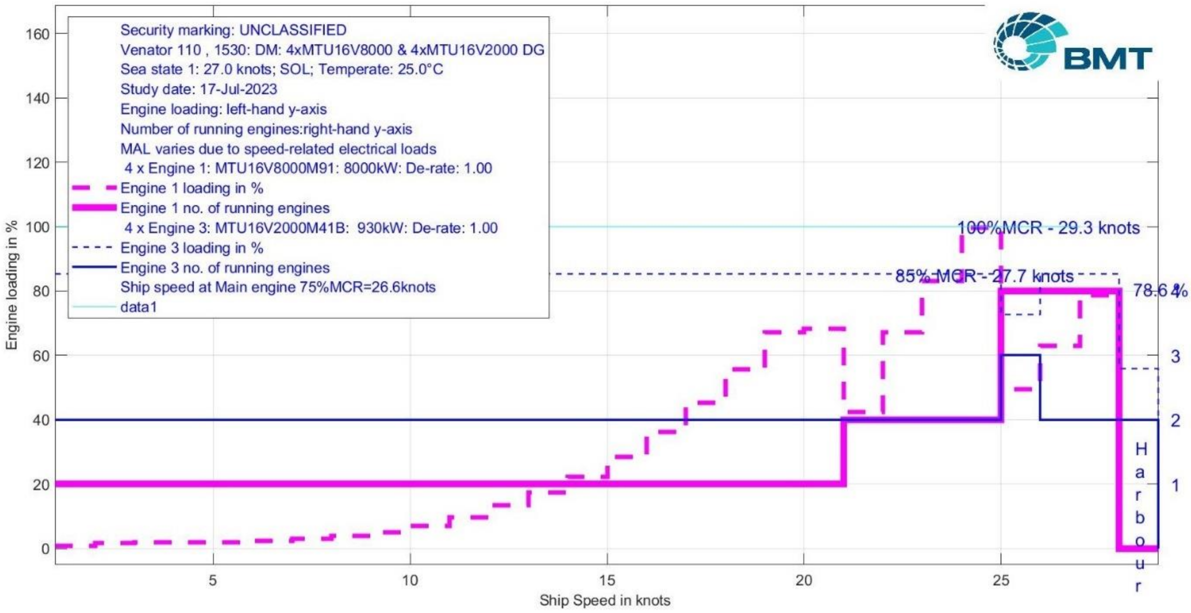

Figure 4. Engine usage & loading across the speed range

In sea state 1, the vessel is driven by one main engine on one shaft with the other propeller blades feathered at speeds up to 20 knots. At speeds from 21 to 24 knots, two shafts are employed with one main engine driving each one. At 25 to 27 knots, all four main engines drive the vessel.

4. Energy Saving Technologies

The 1970’s oil crisis due to political turmoil in the Middle East led to a spate of activity in the shipping world whereby much effort was made to mitigate the large increase in the price of oil by measures to reduce its consumption at sea. That burst of innovation activity subsided as oil prices fell but the Wing Sails And Flettner Rotors that had been developed during this period have now been updated, revised and are increasingly introduced to the commercial marine in ever larger numbers.

5. Wind Propulsion

Among those EST measures there were several based on wind propulsion including square sails (much favoured in Japan, (Yasuo Yoshimura, 2016)), wing sails (especially the Walk Wing Sail, (Walker, 1985)) & (J G Walker & P M Bonney, 1986) and 36m Flettner Rotors (FR) which were fitted to the Maersk Pelican in 2017.

(Bergeson, 1985) researched the effect of a range of wind devices such as standard sails, FR, Turbo Sails (TS) and Wing Sails (WS) over the period 1979 to 1985 with an analysis of their behaviour with vessels of 20,000 DWT.

In 1983, the Wind Ship company for whom Bergeson and Greenwald worked, put a 7m FR to sea on an 18 tonne,42-foot motor cruiser, TRACKER. The trial supported the earliest predictions by Flettner that lift coefficients of 13 are achievable (at speed ratios of ~10), compared to 2.0 for WS (at that time).

One of the unique features of the FR is its inherent load limiting characteristic which can result in a virtually storm-proof sail system. Anton Flettner discovered that in using the Magnus Effect to achieve a novel sailing device, he had also created a virtually storm-proof system, whereby the total (sail) force exerted by the wind on the spinning cylinders did not increase as the wind speed increases. Thus a vessel with FR is able to sail through storms where conventional sailing rigs had to ride out with "bare poles".

Figure 5 shows the relationship in the Magnus Effect between the lift coefficient and the ratio of cylinder surface velocity (circulatory or spin velocity u) to apparent wind velocity (v). If the spin velocity is limited to some absolute maximum value (often 300rpm), any increase in wind velocity results in a decrease in the speed ratio and hence, the lift coefficient. Since the lift force is a function of both lift coefficient and the apparent wind velocity, the two changes tend to cancel each other, resulting in a near “storm-proof” sailing vessel.

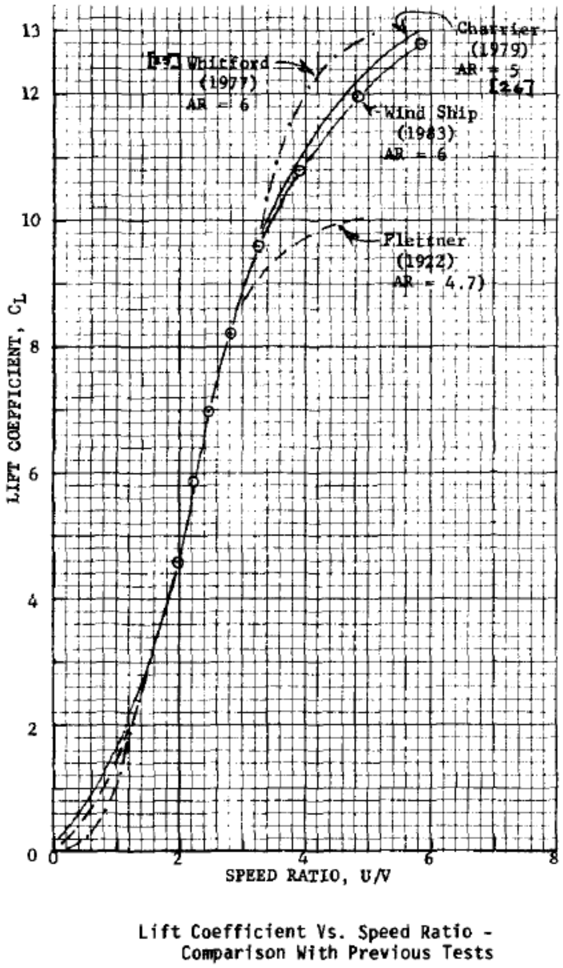

Figure 5. Lift coefficient v speed ratio ((Bergeson, 1985) Fig53)

BMT has spent over 20 years developing its tools and methods for analysing P&P systems, (Buckingham, 2000). The methods have been developed further in recent years after a spell of collaboration with the UK Energy Technologies Institute (ETI), (Buckingham & Pearson, 2018). Specifically, methods were developed that allowed ship-data to be used to drive modelling and simulation of the propulsion system so that the benefits of an EST could be derived from a retrospective analysis, (Buckingham, et al., 2019).

BMT has already undertaken analyses into the fitting of wind propulsion onto warships, (Buckingham, 2021). These exploratory studies build on that work so that key areas for further research can be identified.

6. Flettner Rotor Fit

Three 15m tall FR, each of 2.5m diameter, were fitted to the Venator 110 design. They were located on the after superstructure as depicted in Figure 6. This exploratory arrangement does not account for uptakes, downtakes and the specific requirements of mission systems equipment.

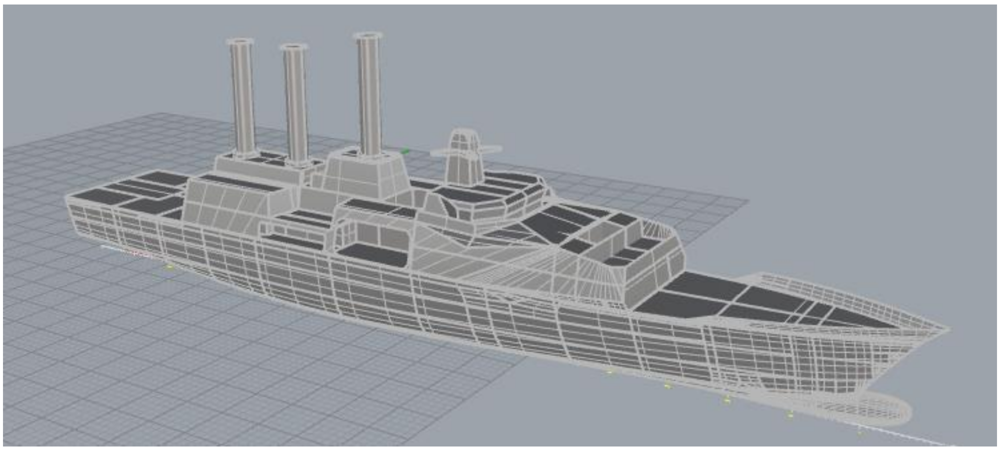

Figure 6.Venator 110 with three 15m Flettner Rotors

The two aftermost FR are located on the hangar roof and the forward one is located on major super-structure. It is recognised that such FR will affect the flow regime of air across the Flight Deck and studies would have to be undertaken to see if the rotating FR could help regulate the turbulence that is normally associated with this arrangement.

The forward Bridge location of a warship means that the FR do not cause any issues with visibility from the Bridge. Figure 7 shows the speed and force vectors for the FR fit in n sea state 4. The vessel is at 15 knots and the indicated True Wind Angle (TWA) is 100° off the bow

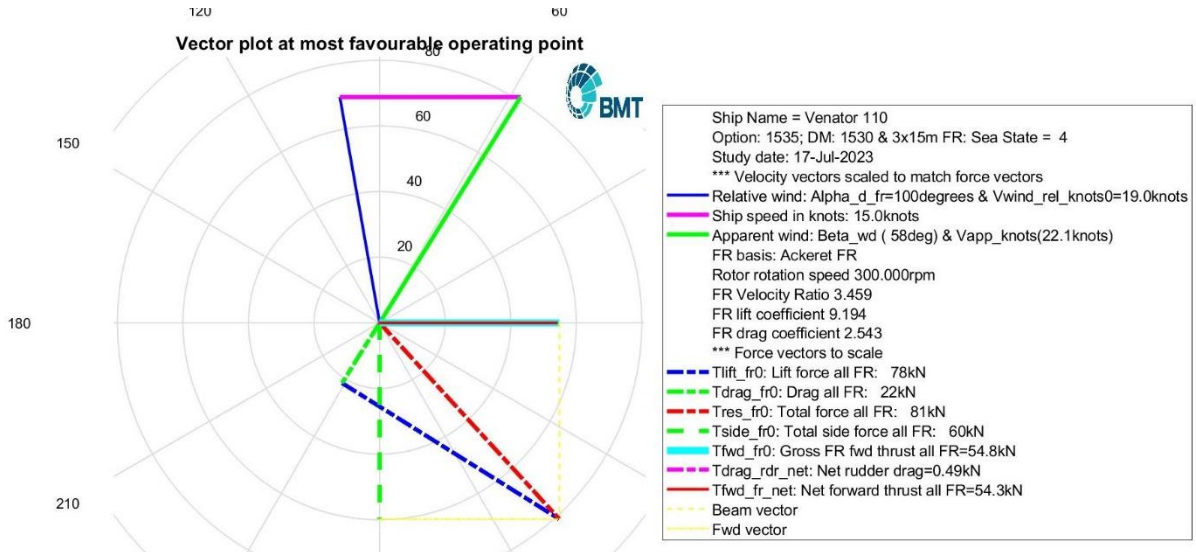

Figure 7. FR speed and force vector polar plot

The set of full azimuth forward thrust values as shown in the polar plot in Figure 8 are averaged to get the value used for these studies which are shown in the legend caption below.

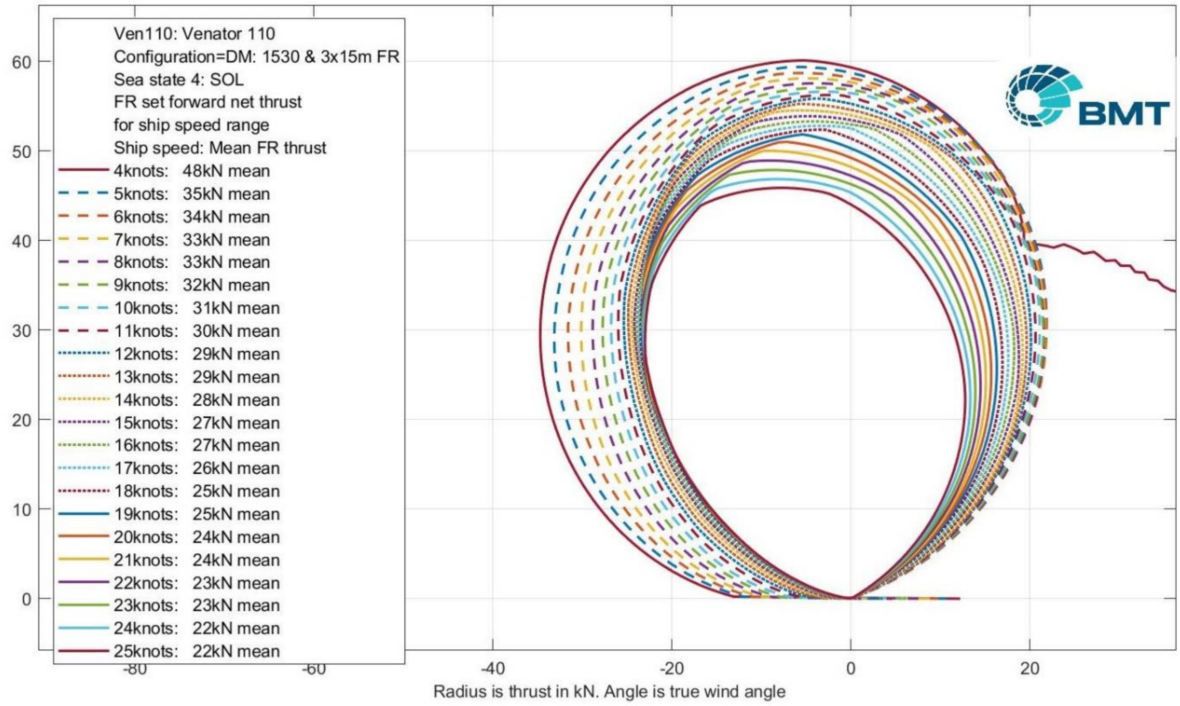

Figure 8. Polar plot of forward thrust for the range of TWA at SS4

The average value of forward thrust shown in the legend entry in Figure 8 is typically 50% of the maximum value achieved. At low ship speeds, the TWA at which maximum forward thrust is generated is just aft of the beam. As the vessel's speed increases, that point moves aftwards slightly. At higher ship speeds, the useful range of TWA decreases from ±50° off the beam to closer to +30° to -45°. The observation is that there is a wider cone of useful TWA when the ship is at slower speeds.

As the ship speed increases, the mean value of the full azimuth set of forward thrust values at each ship speed tends to fall from 48kN at 4 knots to half that at 20 knots. At the most common speed of 12 knots, the forward thrust is 29kN or 62% of the maximum at 4 knots.

Figure 9 shows how the forward thrust varies with TWA and the set of sea states 1 to 6, for the ship moving at 12 knots.

As the sea state increases, the wind speed increases and the wave height increases. The set of sea states are related to open ocean conditions in the North Atlantic and are defined in STANAG 4194, (NATO, 1983) Table D-1 as shown below.

Sea State Number	Significant Wave Height (m)		Sustained Wind Speed (Knots)*		Percentage Probability of Sea State	Modal Wave Period (Sec)	
	Range	Mean	Range	Mean		Range**	Most Probable***
0-1	0-0.1	0.05	0-6	3	0.70	—	—
2	0.1-0.5	0.3	7-10	8.5	6.80	3.3-12.8	7.5
3	0.5-1.25	0.88	11-16	13.5	23.70	5.0-14.8	7.5
4	1.25-2.5	1.88	17-21	19	27.80	6.1-15.2	8.8
5	2.5-4	3.25	22-27	24.5	20.64	8.3-15.5	9.7
6	4-6	5	28-47	37.5	13.15	9.8-16.2	12.4
7	6-9	7.5	48-55	51.5	6.05	11.8-18.5	15.0
8	9-14	11.5	56-63	59.5	1.11	14.2-18.6	16.4
>8	>14	>14	>63	>63	0.05	18.0-23.7	20.0

*Ambient wind sustained at 19.5 m above surface to generate fully-developed seas. To convert to another altitude, H_2, apply $V_2 = V_1(H_2/19.5)^{1/7}$

**Minimum is 5 percentile and maximum is 95 percentile for periods given wave height range.

***Based on periods associated with central frequencies included in Hindcast Climatology.

REVISED MARCH 1984

Table 3. STANAG 4914, Table D-1. NATO SEA STATE NUMERAL TBALE FOR THE OPEN OCEAN NORTH ATLANTIC

The higher forward thrust is generated when the TWA moves towards the stern quarter from the beam.

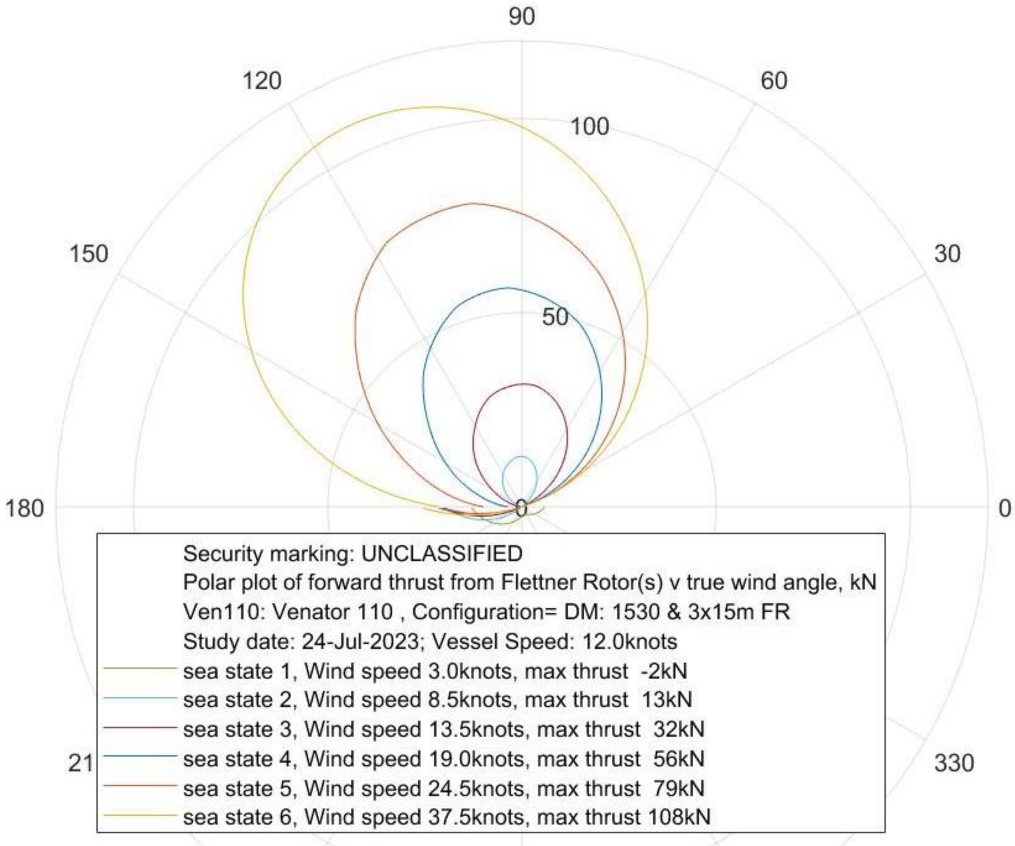

Figure 9. Polar plot of 3FR forward thrust for sea states 1 to 6 for a 12 knot ship speed

The fuel saving for the set of wind speeds associated with sea states 1 to 7 are compiled in Figure 10. This is a plot of percentage fuel difference to the baseline (z-axis) on wind speed (y-axis) versus ship speed (x-axis). Negative fuel difference indicates saved fuel. Sea states 8 and 9 are not shown here as they are both relatively rare in occurrence and when they do occur, the primary consideration is ship safety, not fuel economy.

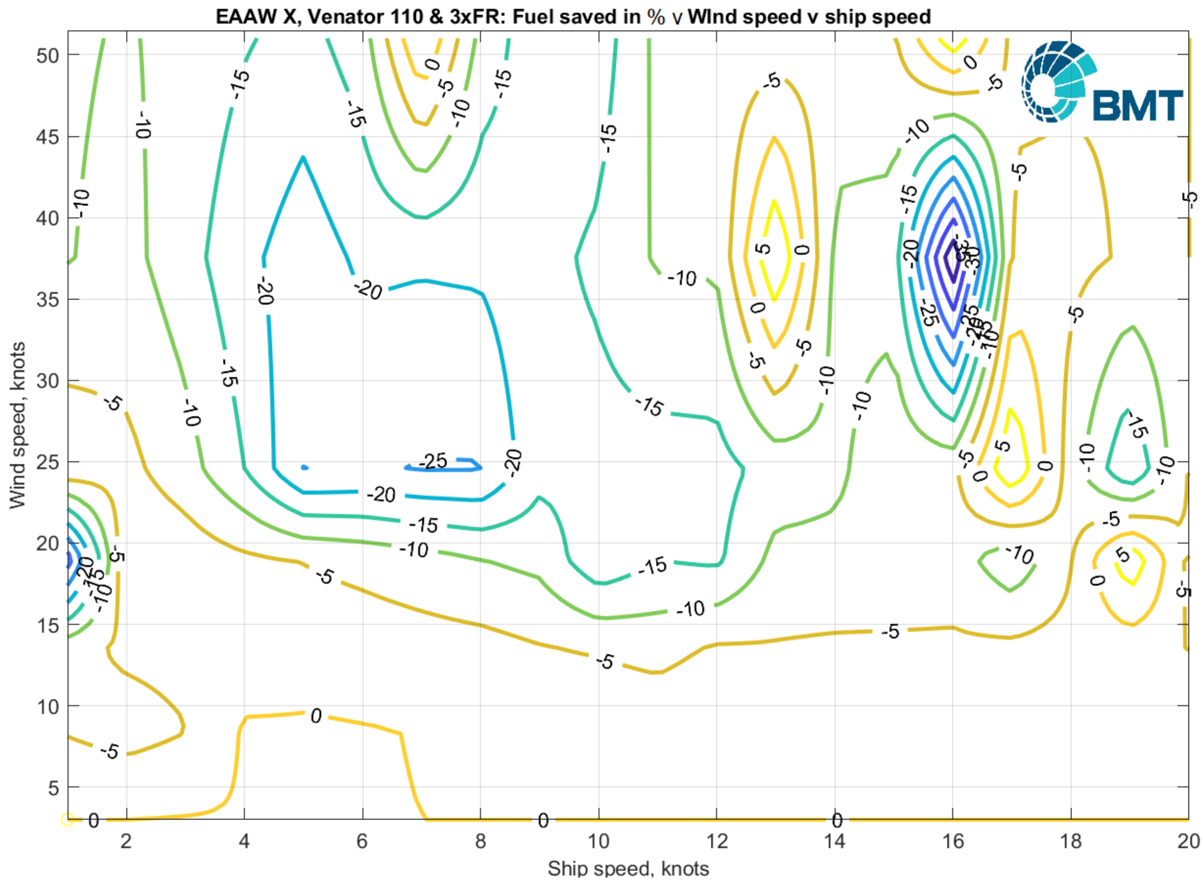

Figure 10. Fuel saved on wind speed (SS1-7) v ship speed

Figure 10 shows that meaningful fuel saving of 5% or more occurs with wind speeds of 15 knots or more at ship speeds above 8 knots and under 18 knots. With wind speeds above 22 knots there are 5% fuel savings at ship speeds between 3 and 20 knots.

There is a particular *sweet-spot* at ships speeds between 4 and 8 knots and wind speeds between 20 and 35 knots, where more significant savings can be realised. However, at these lower speeds, the actual fuel consumption is already quite low and is comparable to that for the SEL.

The poor fuel difference at 36 knots wind, 13 knots ship is due to the effect the FR thrust has on the change-over from single propeller, single engine drive to twin propeller, twin engine drive. Likewise there is a beneficial fuel saving difference at the same wind speed at 16 knots. As is often the case, the command would choose a patrol speed which matches the best engine loading and the average effect win this region would likely be a fuel saving of 10%. When the time spent at different sea states in the North Atlantic is considered and factored, the overall fuel saving is 6%.

Microbubble Drag Reduction

The earliest use of air lubrication systems (ALS) is related to the measures taken by the US and UK navies to use air bubbles in the sea space under the machinery spaces of their vessels to attenuate the dispersion of Underwater Radiated Noise (URN).

Since 1990, extensive studies on drag reduction using micro-bubbles have allowed their effectiveness to be assessed, (Fontaine, 1992). In this approach, air bubbles of between 2mm and 6mm diameter are injected into the boundary layer of ships. The method has been designated Micro-Bubble Drag Reduction (MBDR) and is now offered by a number of shipyards and specialist suppliers such as Silverstream Technologies and Alfa Laval (Marine Performance Limited) as OceanGlide.

A full-scale experiment on the method was carried out by (Nagamatsu, 2002) who measured the local void ratios by taking photographs of air bubbles across the boundary layer of a full scale ship. The ship operated in a range of sea-states. Wu reported on his studies on the numerical simulation of micro-bubble flow around an axi-symmetric body", (Wu, 2006).

(Kodama, 2002), (Kato, 1999), and (Nagamatsu, 2002) described in detail a full-scale micro-bubble experiment carried out using a cement carrier called the 116m long *Pacific Seagull*. In the experiment, propeller thrust and torque, injected air rate, local skin friction, local void ratio, bubble trajectories, and stern vibration were measured. It was found that bubbles entrained into the working propeller slightly affected the propeller performance but, by carefully choosing the point of air injection, bubble entrainment was avoided and a 3% drag reduction was obtained. The ship then operated in sea state three under ballast conditions and achieved a 7% fuel reduction. The lower specific propeller loading also serves to improve propeller efficiency, so the overall impact on propeller efficiency may be closer to neutral.

Kodama states that the benefits of MBDR are limited to slow to medium speed vessels as the power reduction benefit may be outweighed by the air compressor demands at higher speeds. MBDR resistance benefits are smaller proportionately as wave drag becomes more significant but MBDR systems reduce noise and vibration and there are anecdotal reports that they also reduce the onset of hull fouling.

The application of MBDR is usually favoured with vessels with a high block coefficient and hence a larger flatter hull bottom. Warships have a much finer hull and so the scope for the fitting of MBDR equipment to the hull is limited to the smaller flat area. In this study it is assumed that one third of the wetted surface of the hull can be treated with the ALS. The air bubble sizes are assumed to be 6mm with the flow regime assumed to be as defined by (Kodama, 2002) with reduction in viscous friction of 20-30%. The results are therefore considered as conservative as there has been much progress with ALS technology and a much improved understanding of the matching of the ALS to the hullform in recent years. A recent publication states that a reduction of 50-75% of viscous friction is possible with fuel savings up to 12%, (Alfa-Laval, 2023).

An allowance has been made for the energy required to drive the air compressors based on actual air compressor power-air delivery rates. The power required is much affected by the static head of the supply points.

The reduction in the ship's resistance with air lubrication in sea state 1 (wind speed 3knots) is shown in Figure 11. The chief speeds at which there are resistance reductions are between 5 and 20 knots with the largest effect of ~10kN at 10 knots (1 tonne-force). The resistance saving diminishes at speeds above 10 knots as the wave making component of resistance becomes a more significant part of the overall hullform resistance.

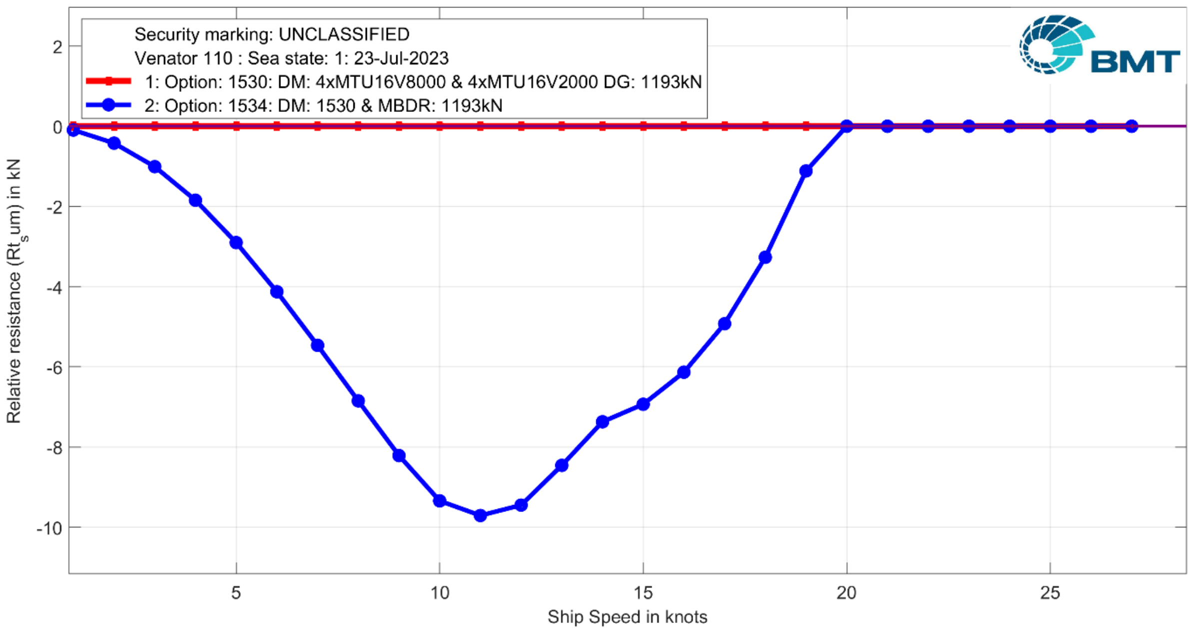

Figure 11. Reduction in ship resistance (kN) at SS1 with hullform air lubrication

For this vessel, the MBDR resistance reduction as a fraction of the viscous friction is about 21% at its maximum point in lower sea states. If a larger hull coverage was feasible, this would increase and in commercial vessels such as tankers and bulkers up to 70% of viscous friction drag is reduced. The MBDR benefits given here are considered to be conservative as in practice the MBDR system would be optimised to suit the vessel's hullform and its operating profile more closely.

Figure 12 shows how this reduced resistance is translated in changes to the fuel consumption in percentage terms at sea state 1.

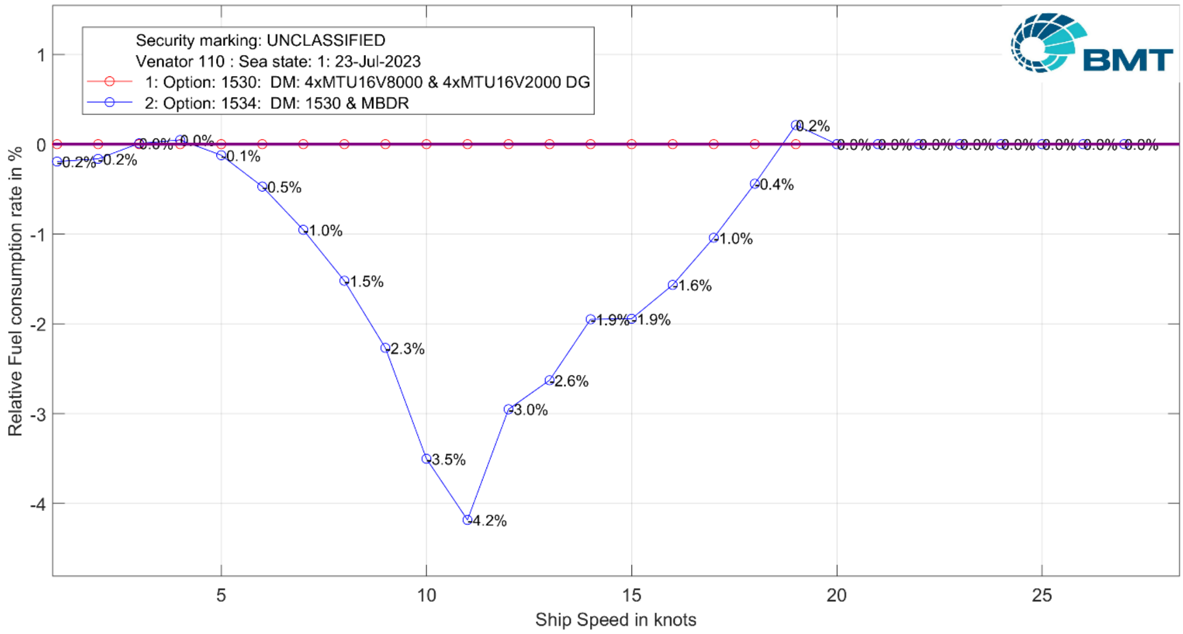

Figure 12. Fuel Consumption for sea state 1 relative to baseline in %

The change in fuel consumption over the speed range mirrors that of the change in resistance. Note that at 19 knots the power to drive the air compressor exceeds the overall benefit of the hull form reduction and so in this case, the ALS is turned off at speeds above 19 knots. When the operating profile is applied the overall annual fuel saving is 0.9% in sea state 1.

Figure 13 shows the contours of fuel saving in % on wind speed v ship speed with the MBDR. At speeds below 5 knots, the energy to drive the air compressors also exceeds the benefit of the air lubrication. In practice the air lubrication would be turned off at such a condition. The worse performance at the lower speeds therefore lowers the overall annual saving estimate.

The greatest savings are at ship speeds between 8 and 14 for most wind speeds up to 35 knots.

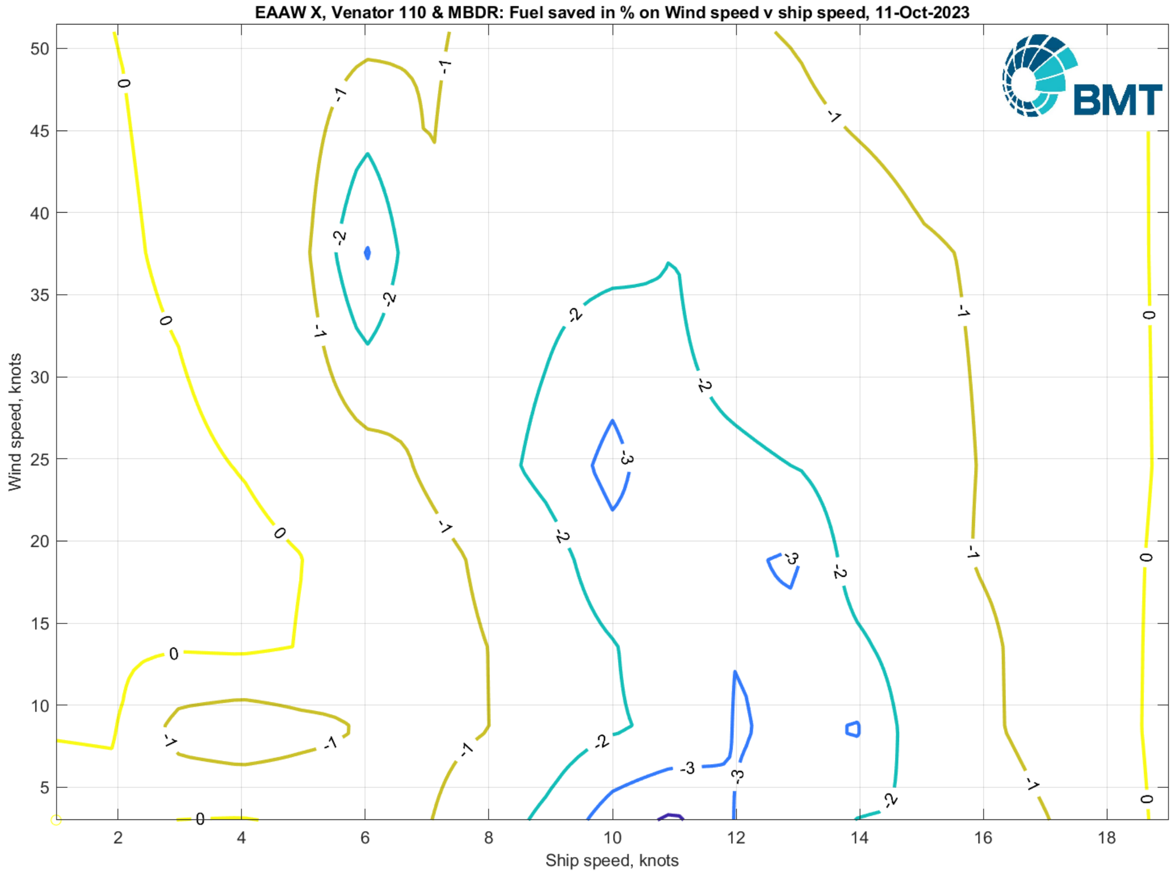

Figure 13. Fuel saved (%) with MBDR on ship speed v wind speed

As the added resistance due to waves increased with increasing sea state, the viscous friction component is a smaller part of the total resistance and the scope for fuel savings diminishes with increasing sea state.

With the operating profile and the time at sea considered, the adoption of MBDR leads to an annual saving of 1%, or 76 tonnes pa. However, as Figure 12 and Figure 13 show, the savings are very dependent on the operating profile as there is a peak beneficial point near 10 knots which could increase this to over 2%. This observation may affect the chosen ship speeds as often ships speeds will be selected to meet a more economic speed of advance.

When the time spent at different sea states in the North Atlantic is considered and factored, the overall fuel saving is 0.5%.

6. Operations with Combined EST

When FR and MBDR are both combined for use on the Venator 110, the hull resistance is reduced as shown in Figure 14.

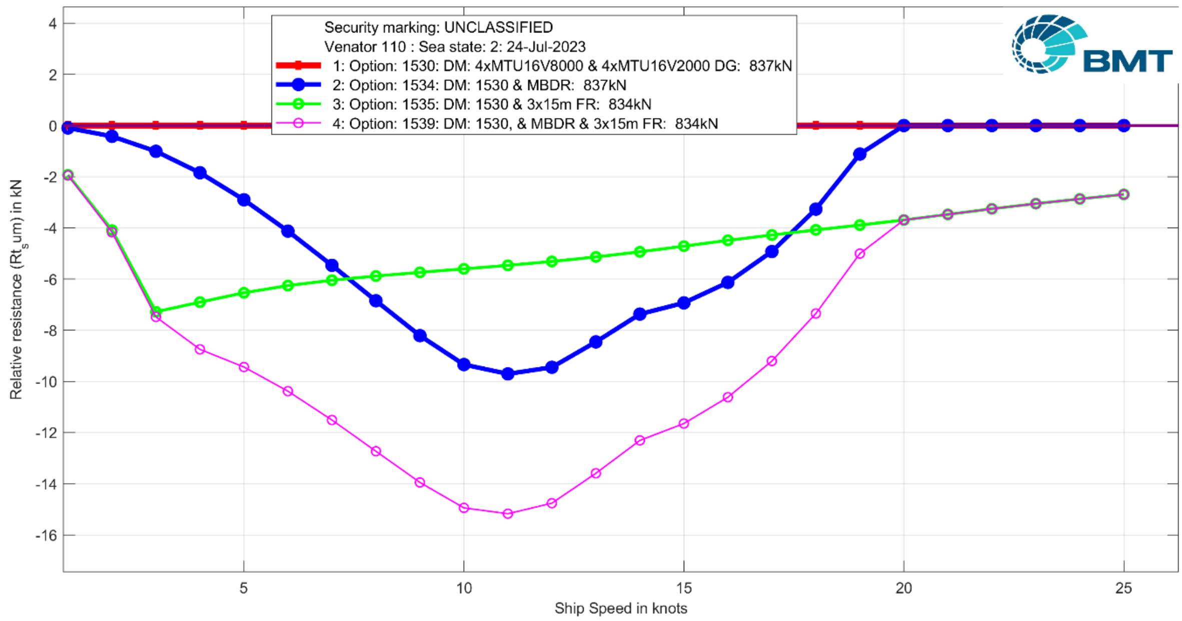

Figure 14. Reduction in ship resistance (kN) at sea state 2 with 3xFR and MBDR (line #4)

Figure 14 shows that at sea state 2 the MBDR benefit complements that of the FR to give a combined benefit of over 10kN reduction in hull resistance between 5 and 16 knots.

When the time spent at different sea states in the North Atlantic is considered and factored in, the overall fuel saving with both EST in use is ~6.5%. This is far below the 40% target for carbon intensity set by the IMO.

7. Alternative Fuels

Measures such as drop-in fuels to (BS.EN.15940, 2023)(i.e. paraffinic diesel oil replacements, also known as Hydrogenated Vegetable Oil (HVO)). A 50% component of HVO to BS EN 15940 into F76 naval fuel oil, (MoD, UK 2004), would reduce the well-to-wake CO_2 emissions by 45%. As the RN consumes about 200,000 tonnes of F76 per year, (Olivier, RCN, 2008), 100,000 tonnes of BS EN 15940 could be used as a drop-in with relatively little impact on the specification. The chief area to address would be the flash point of the 50-50 mixture and the reduced mass density and hence the reduced energy density which would affect the standard range of the vessel.

In November 2020, the RAF revised its aviation fuel standards to allow up to 50% of qualified sustainable fuel drop-ins for all its aircraft. We are in the first epoch (2021-2025) of the UK MoD strategy for climate change and sustainability, (MoD, UK, 2021). Step changes to current programmes are permitted to allow the necessary changes to be fed into the infrastructure and platforms that the MoD will use for decades to come. Carbon targets are to run through the yearly Defence Plans and although there is now a need to baseline and document current emissions, this should not delay the actions required to reduce emissions!

The IMO MEPC 80 meeting in July 2023, (IMO, 2023) announced, “a commitment to ensure an uptake of alternative zero and near-zero GHG fuels by 2030”, The carbon intensity of international shipping is to decline to reduce CO_2 emissions per transport work, as an average across international shipping, by at least 40% by 2030, compared to 2008. The commitment states that the uptake of zero, or near-zero, GHG emission technologies, fuels and/or energy sources is to represent at least 5%, striving for 10% of the energy used by international shipping by 2030.

Therefore, designs and plans need to be made now for ship fit in the coming few years. Much will be learnt from early projects where EST are fitted to warships and naval auxiliaries. Such valuable lessons will lead to a better and more cost-effective set of changes thereafter.

It is convenient to say that Defence should be a fast follower with international shipping and its infrastructure to lead the way for alternative fuels and EST. However, Defence is always a special case with the need for safe and inter-operable fuels between allies and co-operating partners, and so it needs to own and manage its own destiny and the transition towards it. Paraffinic fuel to BS EN 15940 as a drop-in fuel is an obvious choice for the UK to make the short-term fuel changes which are already allowed by many marine diesel engine suppliers.

8. Sail-Vessel Interaction

The interaction of the effect of wind propulsion devices such as sails is a long held science relating to the way in which the best effects can be elicited from them for all angles and all wind speeds for any given ship speed. The modelling and analysis of this aspect have been addressed by (JJ Jensen, 2004) who sought to define and quantify the principal coefficients relating to the motions in the six degrees of freedom a vessel in a closed-form fashion. Using basic empirical and derived coefficients, Jensen identified suitable working estimates of the vessel's principal roll and heel factors and coefficients. These are part of a force-balance model of the vessel and the wind device which is used in a time-based analysis of the interactions and effects of the sideways forces of a wind propulsion device upon the vessel.

The roll moments were identified from the following elements references are to (JJ Jensen, 2004):

- Likely rolling forces to ambient sea states (Section 6.3, equation 6.14)
- Side force due to wind on ship's hull;
- Damping action of water on hull (Sections 6.2 & 6.4)
- Inertial effect of hull's own inertia mass;
- Restoring vessel's moment using the restoring moment coefficient which is a function of the transverse metacentric height.

In addition to these is the sideways force of 60kN from the 3xFR in sea state 4 when the TWA is 100° (See Figure 7).

The analysis has also considered the loss of rolling moment as the vessel rolls away to the leeward side away from the forces due to wind and wave. The time-plot analysis of the vessel's rolling motion in sea state 4 is shown in Figure 15. This is to be considered as an example of the roll behaviour as the true behaviour will be much more complex.

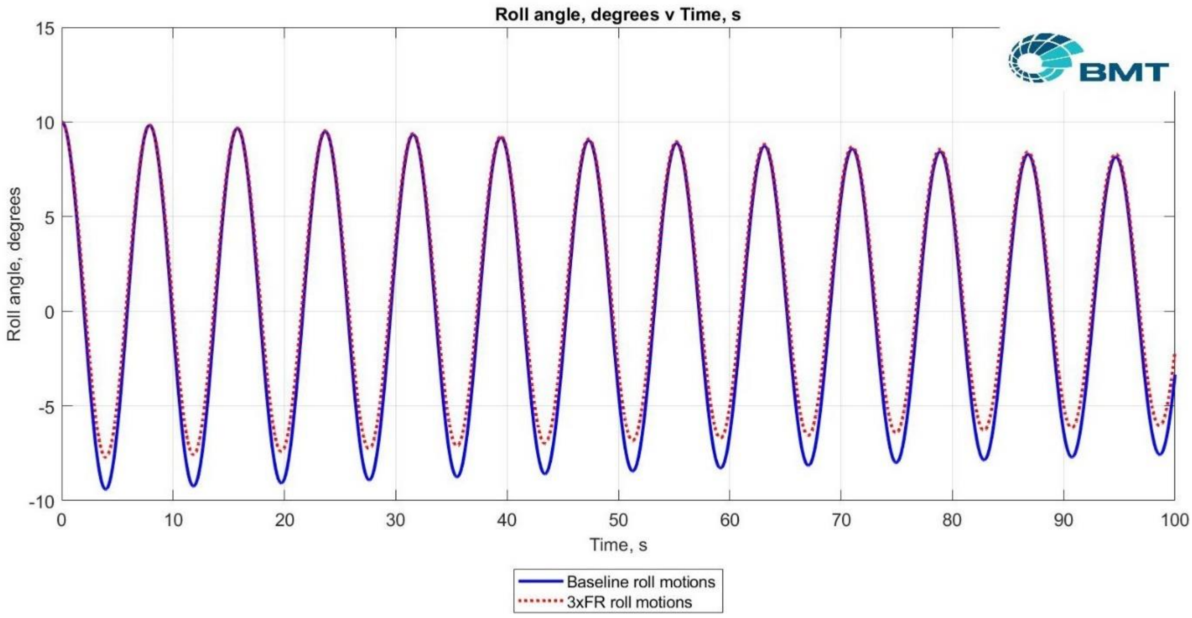

Figure 15. Typical rolling motion in SS4 for vessel with (red dotted) and without (blue) 3xFR

The figure shows how the extra side force due to the 3xFR has relatively little impact on the lee roll compared to the baseline, but the roll into wind leads to a reduced roll angle of the order of 1.5° (15%). Although this is not a major impact on vessel seakeeping, this effect may help reduce the air lost from the ALS in such a sea state and may then help preserve the benefit of ALS in such cases. Any reduction in roll will also lead to a reduced requirement for the rudder to operate to maintain heading. This too may therefore help reduce URN and energy consumption.

9. Other Considerations

These studies have considered the wind speed to be constant with height at the point of contact with the vessel, and the changes to the wind flow regime as it passes over the ship's side are also not factored in. Whilst previous work has shown this aspect to be specific to each design, (W Hopes, 2021), the ship's behaviour and the ambient sea and wind conditions, it is likely to reduce the effectiveness of the FR due to the inconsistent flow path over the FR along its height.

10. Conclusions

BMT has undertaken theoretical studies into the combined effect of wind propulsion and hull air lubrication on its Venator 110 frigate design. These studies have been summarised in this conference paper to present the principal outputs and the informed insights they provide.

Wind propulsion offers significant benefits (>5% fuel saving) at sea states 3 (13.5 knots) and above but in the major shipping lanes, such operating conditions are mainly found in northern Europe and the North Atlantic, ALS offer a consistent benefit whatever the wind conditions and when the vessel slows down due to increased sea states, there are still tangible benefits.

The combined effects of wind propulsion and air lubrication EST lead to a conservative estimate of 6% reduction in fuel and hence, GHG emissions compared to the baseline design. This exceeds the 5% minimum target set in July 2023 by the (IMO, 2023).

However, for more ambitious reductions in GHG emissions, there needs to be the adoption of a drop-in fuel such as HVO to EN15940 which is already compatible with many four-stroke marine engines up to high fractions. However, the operator of Venator is to engage with the supply chain of any alternative fuel so that the "well-to-tank" component is factored into the total life-cycle assessment as is now required by IMO, (IMO, 2023).

11. Acknowledgements

The author would like to thank BMT for providing the resources necessary to allow this research to be undertaken and presented. The views expressed in this paper are that of the author and do not necessarily represent the views and opinions of either BMT or any other agencies such as the MoD.

Thanks also to those who have carefully reviewed the paper and provided value feedback. All errors are my own.

12. References

Alfa-Laval, 2023. *OceanGlide: Sail Into the Future.* s.l.:s.n.

Bergeson, G., 1985. *Sail Assist Developments 1979-1985.* s.l., Journal of Wind Engineering & Industrial Aerodynamics.

BMT, 2016. *Venator 110 - The Technical Brief,* Bath, UK: BMT.

BS.EN.15940, 2023. *Automotive fuels. Paraffinic diesel fuel from synthesis or hydrotreatment. Requirements and test methods,* s.l.: BSI.

Buckingham, J., 2000. *Ptool: Fast performance and cost modelling of propulsion powering systems.* Paris, AES 2000.

Buckingham, J., 2021. *Potential Energy Saving Technologies for the Type 23 Frigate.* UK, MOD Defence Sustainability Conference.

Buckingham, J. & Pearson, D., 2018. *Modelling the Performance of Energy Saving Technologies on Ships.* London, RINA Full Scale Ship Performance.

Buckingham, J., Pearson, D. & Storey, E., 2019. *SHIP DATA DRIVEN PROPULSION MODELS & WIND-BASED PROPULSION TECHNOLOGY.* London, UK, RINA Wind Propulsion Conference.

Fontaine, A. e. a., 1992. *“The Influence of the Type of Gas on the Reduction of Skin Friction Drag by Microbubble Injection,”.* s.l., Experiments in Fluids, Springer-Verlag, vol. 13, No. 2/3, pp. 128-136,.

IMO, 2023. *2023 IMO STRATEGY ON REDUCTION OF GHG EMISSIONS FROM SHIPS,* London: IMO.

IPCC, 2022. *The evidence is clear: the time for action is now. We can halve emissions by 2030.* [Online]
Available at: https://www.ipcc.ch/2022/04/04/ipcc-ar6-wgiii-pressrelease/
[Accessed 25 July 2023].

J G Walker & P M Bonney, 1986. *"Walker Wingsail Operating Experience on the MV Ashington".*. s.l., Trans. North East Coast Inst. Engrs. and Shipb., 103 (1986), p. 29..

JJ Jensen, e. a., 2004. *Estimation of shipmotions using closed-form expressions.* Lyngby, DN, Ocean Engineering .

Kato, H., 1999. *“Skin Friction Reduction by Microbubbles”.*. s.l., s.n.

Kimber, A., 2008.1. *Minor Warship Roles - How technology is leading to a new vessel type.* Sydney, Engineers Australia.

Kimber, A., 2008.2. *The globally deployable minor warship - A conceptualisation of future solutions.* Hamburg, IMarEST.

Kodama, 2002. *"Effect of Microbubble Distribution on Skin Friction Reduction".*. s.l., s.n.

MoD, UK 2004. *Def-Stan 91-4, F76 fuel designation, issue 7,* s.l.: s.n.

MoD, UK, 2021. *Climate Change and Sustainability Strategic Approach,* s.l.: s.n.

Nagamatsu, T. e. a., 2002. *A full-scale experiment on microbubbles for skin friction reduction using SEIUN MARU Part 2: The fullscale experiment.* s.l., Journal of the Society of Naval Architects of Japan 192, 15-28..

NATO, 1983. *STANAG 4194. Standardized wave and wind environments and shipboard reporting of sea conditions.* s.l.:s.n.

Olivier, J., RCN, 2008. *“UK navy surface warships engines exhaust emissions study 1988-2006”,* s.l.: UK MoD, J.Nav.Eng 44(2).

Stark, 2022. Study on Applicability of Energy-Saving Devices to Hydrogen Fuel Cell Powered Ships. *Journal of Marine Science & Engineering.*.

W Hopes, D. P. J. E. B., 2021. *A CFD Study on Wind Assisted Propulsion Technology for Commercial Shipping.* London, RINA Wind Propulsion .

Walker, J. G., 1985. *‘A High Performance Automatic Wingsail Auxiliary Propulsion System for Commercial Ships.’.* s.l., Journal of Wind Engineering and Industrial Aerodynamics.’ 20 (1985) 83-96. Elsevier Science Publishers B.V., Amsterdam..

Wu, C. e. a., 2006. *Numerical simulation of micro-bubble flow around an axi-symmetric body.* s.l., s.n.

Yasuo Yoshimura, K. O. a. T. W., 2016. *Contributions to EEOI and EEDIby Wind Challenger Ships.* Hong Kong, Proceedings of 7th PAAMES and AMEC2016.