An assessment of the resistance and wake making properties of industry-standard bow designs

Charles E Archer* FdSc

* University Centre South Devon, Paignton, United Kingdom

* Corresponding Author. Email: charliearcher44@gmail.com

Synopsis

In recent years, the focus on Naval Architecture has been towards energy efficient craft. Although efficiency in naval architecture is impossible to be pinned to a singular section, the bow is one of the most important parts of surface ships. The bow not only has a main purpose of cutting through water, but also alters the fluid dynamics to reduce surface friction and resistance across the hull form. This alteration also impacts the wake and disturbance produced. Newer bow forms, such as the X-BOW®, are taking the conventional shape and inverting them to produce more efficient designs for strong ocean conditions. Whereas other new designs are altering bow shape to focus directly on wave piercing technology. This paper uses Maxsurf® software, to analyse the resistance and wake making properties of six industry-standard bow designs available on market: the X, Axe, Maier, Conventional, Plumb and Vertical bow. The paper also addresses the possibility of using the most efficient design on military surface ships and its place in naval architecture.

Keywords: Naval Architecture, Resistance, Bow, Wake, Shipping, Maxsurf®

Biography

Charles Edward Archer is an undergraduate Composite Instructor for Princess Yachts Ltd and South Devon College. Interested in Composite techniques and naval architecture, he has received a Foundation Degree in Marine Technologies from University Centre South Devon. He continues to research more efficient naval designs and technologies to achieve his bachelor's degree.

1. Introduction

In an industry where cost and environmental concerns are increasingly important it is essential for boats to be as efficient as possible. This increases fuel efficiency, thus reducing the emissions from the vessel when under way. With the tightening of rules and regulations protecting the environment, boat designers must research all possible ways of reducing resistance and increasing efficiency. In the specialized field of sail racing, having the most efficient vessel is imperative, as resistance will reduce the key attributes of speed and acceleration.

Used to cut through water and 'designed to reduce wave making resistance' (Wartsila, 2019), the bow is one of the most important parts of a vessel. There are many designs and methods of testing vessel bows. Before the invention of Computer Aided Design (CAD), models were used to test the design of ships' bows and hulls. From the 1860's onwards, these models would be tested in a testing tank. Modern testing tanks come in different types and with the aid of computers and testing programs, designers now use computers to aid the hydrodynamic tests in these tanks. With the invention of hull design and testing software such as 'Maxsurf®', Naval Architects are now able to simulate and test the design of vessels without making a model. Computer simulations can predict various accurate sea conditions and provide detailed statistics on the vessels' performance.

This project will explore the resistance of different types of bow design, when simulated in a calm sea state and analyse the friction caused between the water and 'skin' of the vessel. This project will determine the best design for piercing waves and predict which design is the most efficient in a range of scenarios. The project will also look at the wake patterns created by different types of bow design and evaluate the frequency of the transverse and divergent waves created. Finally, the most efficient design will be critically analysed for potential military applications.

To gather data, CAD software 'Maxsurf®' was used to calculate the resistance on a vessel with different bow designs. Analysing the graphs produced, it is easy to see where resistance builds and at what speed. In an attempt to minimize confounding factors, the same hull will be used with each bow design. Similarly, Maxsurf® will also be used to test and visualise the wake patterns created from each bow design. By doing this, it is possible to see which one has the best wave-piercing properties and therefore highest efficiency.

There are numerous bow designs, from the 'Bulbous Bow' on large cargo ships to the 'X-BOW®' used on Offshore Support Vessels. A survey of the existing literature established the six most prevalent designs (Hassan, *et al*, 2017, Syahril and Nabawi, 2019). The tests could be simulated in many varying sea conditions, for the purposes of this study all designs were tested in one type of sea state. A clam sea state was chosen for the simulation as no bow will perform in favour of this condition.

There are a few considerations which will have to be accepted as true within the context of the study. Firstly, it will be assumed that the computer simulation accurately represents real sea conditions. This can be assumed as various international corporations such as the US Navy use Maxsurf®. Secondly, the methodology employed ignores the possibility that a particular bow shape might imply a different stern configuration. Another assumption that must be made is the scaling down and size of the vessel, it must be assumed that the data produced will be accurate to any size ship.

Resistance on the bow and hull will need to be measured. This will be done by using a simulation software program. This will determine the amount of resistance on varying Bow designs in Kilonewtons (KN). Arguably it would have been useful to have explored the numberless value called the Froude Number *Fr* (see *Appendices 2*), however, this remains an option for future research.

2. Literature review

A ship's bow has a 'significant effect on the ship resistance components, especially wave making resistance' (Hassan, *et al*, 2017). Therefore, it is important to design and test ships' bows to make them as efficient as possible. One way of doing this is by increasing wave-piercing technology which impacts the vessel's wake. This literature review will explore current research on developing the best shaped bow for reducing resistance and wake making properties in order to make a more efficient vessel.

There are many types of bow design, each suited for different roles and applications. 'Normal' or 'bulbless' bows can be described as either a Vertical, Raked or Maier bow forms (see *Figure 1)*. 'The main advantages of Vertical bows are reducing the frictional resistance and easy to manufacture' (Hassan *et al*, 2017). However, the vertical bow makes it easy for water to enter the ship, therefore the Raked and Maier are more popular, due to 'conjunction with V section to reduce frictional resistance… and increase in reverse buoyancy and ship protection in collision' (Hassan *et al*, 2017).

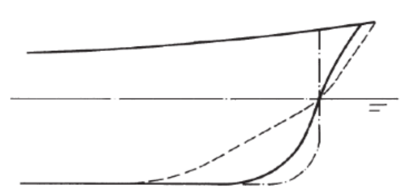


Figure 1 'Normal' bow forms: — Conventional form - - - Maier bow -·-·-·- Vertical bow

The Bulbous Bow, originally developed by David Taylor and used as early as 1907, utilises a protruding bulb located at the bow just below the waterline (see *Figure 2)*. According to Chrismianto, Kiryanto and Adietya (2018) 'the bulb modifies the way the water flows around the hull, reducing drag and thus increasing speed, range, fuel efficiency, and stability'. Because of its ability to 'save the fuel consumption up to 15%' (Liul, et al 2014), it is used on most large cargo ships. However, it has been argued that Bulbous bow effect is useless for ships when waterline length is less than about 15 metres (Hassan *et al*, 2017). This means bulbous bows are ineffective for smaller craft such as yachts. importantly, because the bow protrudes in front of the ship, it can be dangerous in harbours.

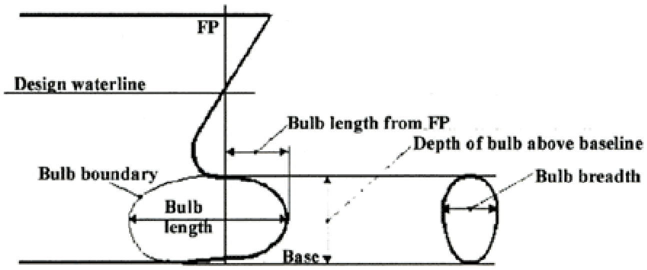


Figure 2: Bulbous bow design

Another significant design is the Inverted bow, commonly implemented on warships during the late 19th century and early 20th century. This design consists of the farthest point being at or below the Design Waterline (DWL), almost completely opposite to the traditional/conventional bow forms. The inverted bow has made a reappearance on Frances' new Frégates de Défense et d'Intervention (FDI) frigate and the Zumwalt-class destroyer produced for the United States Navy. One type of inverted bow is the X-BOW® (see *Figure 3*). Developed in 2005 and designed by the Ulstein Group, consisting of an inverted bow with a sharper entrance through water. Ulstein claims the X-BOW® results in a 'wave piercing effect at small wave heights, and also reduces pitching and bow impact loads in bigger seas' (Ulstein, no date). However, it must be remembered that Ulstein are attempting to persuade potential buyers to invest. Independent sources suggest disadvantages, such as 'X-bow depends on the large inertia of the vessel to help delay pitch motions' (Datawave Marine Solutions, 2018).

Figure 3: The X-BOW® design

The Axe-bow (see *Figure 4*) is a design from Damen shipyard which is claimed to 'exhibit superior motion behaviour and significantly lower resistance through the water. This leads to a cut in fuel usage of 20% and, consequently, lower emissions' (Damen, 2019). Again, this is information produced from the distributor's company, meaning the source is potentially biased. An independent academic report by Keuning, Pinkster and Walree (2002) suggests that the AXE bow needs considerably more rudder motion to keep its track, particularly in steeper waves.

Figure 4: Axe-Bow design on a patrol boat

Analysing a report on flat hull ship bow designs by Syahril and Nabawi (2019), states that ‘the flat hull ship using the type of Raked Bow has the lowest resistance of 314.74 N; the second lowest type of bow is the type of Plumb Bow with the resistance of the ship about 335.44 N’. This report uses a methodology similar to that of the current study. The models were designed and tested using Maxsurf®, the same program to be used in this project. However, only four different bow types were tested and two of these were the ‘Raked’ bow. There is a wide array of bow types that could have been selected such as the ‘Axe or ‘X’ bow. Reviewing a report from Yang and Kim (2016) on resistance on blunt ships with different bow shapes in short waves, it is stated that an Axe bow ‘reduces the added resistance in waves compared to the [original hull form]’. In addition, the research was carried out using computer models of Length 320m and Beam 58m. These are a lot bigger than the computational models to be used in the current research project and the size of the vessel may significantly impact the amount of resistance.

Another possible flaw in the methodology is that the Cartesian-grid method was used to gather data. This is a different data collection method and may have a direct impact on the comparisons between data. Hassan compares the resistance of different hull and bow forms, concluding that:

> Hull with X-bow illustrates that good reduction in wave making resistance where at high Froude number for series 60 with X-bow reduces 16%,for KCS model with X-bow reduces 26% and DTMB 5415 model reduces 49% if compare with the original hull of three reference models (Hassan *et al*, 2017)

This report argues that the X-BOW® exhibits reduced resistance when compared to other bow types. The results were calculated using ‘Maxsurf® Resistance’, the same simulation to be used when collecting data for this project.

This research will take Hassan’s findings as a starting-point and will recreate the X-BOW® design used in his study. It is anticipated that the same results will be obtained. However, this study will go on to use this model to test a wider range of bow designs.

3. Methodology

The research takes a quantitative data approach using computer programs and simulations to accurately predict the outcome of varying design. The core of this project will be a computer simulation study using Maxsurf®, an industry standard design program. Similar Marine Design Software, such as AutoShip® and Rhinoceros® were considered, however, ‘the applications in Maxsurf have a standard Microsoft Windows user interface… which makes them easy to learn and use’ (Maxsurf, 2022). The focus of this project will be the analysis of resistance in a range of bow designs. However, to add depth and context to this research, six different bow types will be tested, at a range of different speeds.

The computer software program Maxsurf® Modeller will be used to design a generic hull and a range of bow types. Once this has been done, the simulation program Maxsurf® Resistance will be used to put the simulated vessels in a virtual sea environment.

Regarding validity, a study was carried out to investigate the correspondence between the accuracy of Froude numbers obtained within a towing test tank and those generated using Maxsurf® Resistance (Jeremy, 2015). It was found that Maxsurf® Resistance had 'small deviations at Froude numbers of 0.28–0.35 and above 0.49 from that of the tank tests' (Jeremy, 2015). Practically speaking these deviations would have little effect. In Bentley's product brochure for Maxsurf®, it is claimed that the 'software has been validated against a variety of data from various independent sources: including model tests, full scale trials and other numerical methods' (Island Computers, no date).

There will be six different bow types tested, the X-BOW®, Axe-bow, Bulbous bow, Maier, Vertical and Raked designs (see *Appendices 3-9*). Because each bow design needs to be situated in the water itself, a planing or semi-planing hull would be inefficient as often the bow raises out of the water. Consequently, a displacement hull was used to test each bow design. To reduce any confounding factors, exactly the same hull design was used in all tests. Because it is argued that Bulbous bow effect is useless for ships when waterline length is less than about 15 metres (Hassan *et al*, 2017), the hull length was set at 20 metres.

The aim of the study is to determine the bow design with the least resistance. The Null hypothesis states that there will be no statistically significant difference in resistance of the different bows. Previous studies suggest that the X-BOW® will have lower resistance than the Vertical bow at all speeds. It is therefore anticipated that the data from this study will provide sufficient evidence to reject the null hypothesis.

There will be many variables in the computer simulation tests. Firstly, the resistance will be determined using the 'Holtrop and Compton calculations for fast displacement hulls' (Maxsurf, no date). This method is appropriate because the hull selected is a displacement type and the bow designs will be tested at variable speeds.

Wake will be calculated by analysing the pattern and using the rendering feature to locate wave and elevation contours. This will allow easy analysis of the disruption created in the water.

The quantitative data will be calculated and collected using a computer simulation. Maxsurf® Resistance will be used to find this data and will automatically calculate the variables needed.

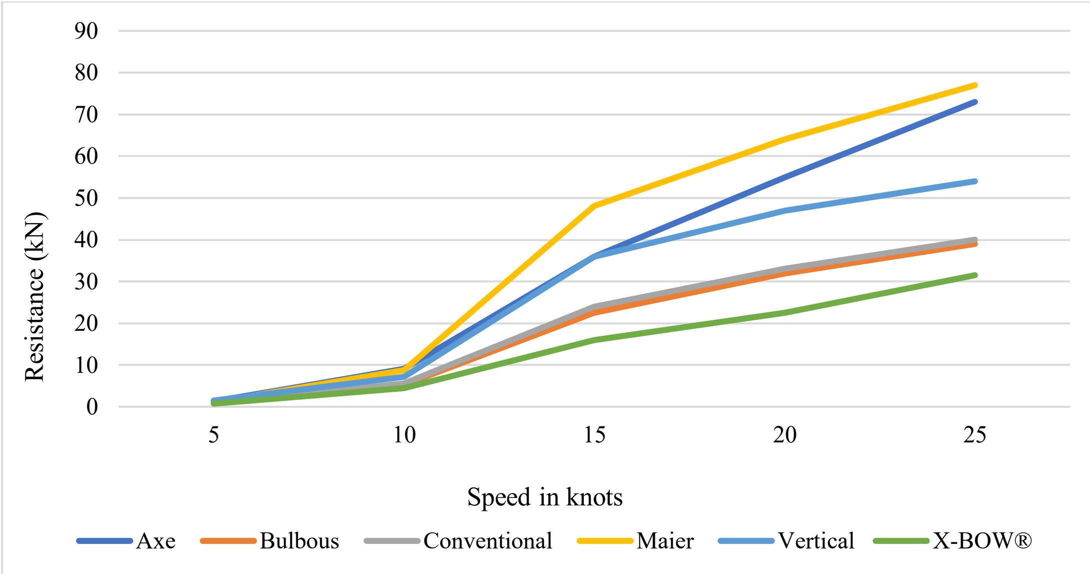
The results section will present a graphical representation of speed against resistance for each of the bow designs. These graphs will be used to investigate the null hypothesis. If this hypothesis is rejected, further analysis using the Mann-Whitney method will be undertaken to explore the difference between specific bow designs.

4. Results

The results summary is detailed in the table below.

Speed in Knots	**5**	**10**	**15**	**20**	**25**
Type of Bow	Resistance (kN)				
Axe	1.3	9.1	36	55	73
Bulbous	0.95	5.3	22.5	32	39
Conventional	0.97	5.5	24	33	40
Maier	1.1	8.7	48	64	77
Vertical	1.5	7.1	36	47	54
X-BOW®	0.75	4.5	16	22.5	31.5

Table 1: Maxsurf® results.



Graph 1: Maxsurf® results

In summary, the performance of the bows can be described as follows:

The graph data collected shows the amount of resistance in kN against the speed of the vessel in Knots.

- **Axe Bow**: At low speeds (5-10 Knots), the resistance and speed increased steadily until 8 – 9.5 knots, when resistance rapidly increased. At medium speeds (10-20 Knots), a steady increase occurred in resistance as speed increased, until 17 knots where the increase in resistance started to drop off. At High speeds (20 – 25 Knots), the resistance and speed created a direct proportion gradient.
- **Bulbous Bow**: At low speeds (5-10 Knots), the resistance and speed increased steadily until 8 – 8.8 knots, when resistance rapidly increased. At medium speeds (10-20 Knots), a rapid increase occurred in resistance as speed increased between 11-16 knots, from 16 knots the increase in resistance started to drop off. At High speeds (20 – 25 Knots), the resistance had a gradual positive incline.
- **Conventional Bow**: At low speeds (5-10 Knots), the resistance and speed increased steadily until 8.5 – 9 knots, when resistance rapidly increased. At medium speeds (10-20 Knots), a rapid increase occurred in resistance at 11 – 15 knots, after which resistance reduced to a gradual positive incline. At High speeds (20 – 25 Knots), the resistance and speed created a direct proportion gradient.
- **Maier Bow**: At low speeds (5-10 Knots), the resistance and speed increased steadily until 7.5 – 9.2 knots, when resistance rapidly increased. At medium speeds (10-20 Knots), a rapid increase occurred in resistance at 10.5 – 16 Knots, before easing into a direct proportion gradient. At High speeds (20 – 25 Knots), the resistance had a gradual positive incline.
- **Vertical Bow**: At low speeds (5-10 Knots), the resistance and speed increased steadily until 7.5 – 8.5 knots, when resistance rapidly increased. At medium speeds (10-20 Knots), a rapid increase occurred in resistance at 11 – 18 Knots. At High speeds (20 – 25 Knots), the resistance and speed created a direct proportion gradient until 22 knots where the resistance had a gradual positive incline.
- **X-BOW®**: At low speeds (5-10 Knots), the resistance and speed increased steadily creating a gradual positive incline. At medium speeds (10-20 Knots), a rapid increase occurred in resistance at 10.5 – 15 Knots, onwards a direct proportional gradient occurred. At High speeds (20 – 25 Knots), the resistance and speed created a direct proportion.

The wake can be shown by using the rendering visualisation aid provided by Maxsurf® (see *Appendices 10-15*). The descriptions of the wake along the waterline of the boat are given in *Appendices 1*.

5. Discussion

This section will discuss the quantitative data gathered over the course of this study. The research hypothesis and null hypothesis will be explored. The data gained will then be compared to previous research and threats to validity will be discussed. In addition, the suitability of the most efficient bow design will be analysed in the context of potential military applications.

The null hypothesis stated that there would be no statistically significant difference in resistance of the different bows. Each of the six bow designs produced a different resistance, such as the Bulbous bow at 5 knots (0.95Kn) against the Axe bow at 5 knots (1.3Kn), producing sufficient evidence to reject the null hypothesis. Referring to the research hypothesis that the X-BOW® will have lower resistance than the Vertical bow at all speeds, the data acquired in Table 1 (*page 14*) supports this hypothesis. At 5 knots of speed, the vertical bow produced 1.5Kn of resistance compared to the X-BOW® which produced 0.75, exactly half. This trend continued throughout the varying speed of 10-25 knots, supporting the research hypothesis. The research carried out, further added to the validity of Hassan *et al's* (2017) findings in bow design. Ultimately the research was able to clearly reject the null hypothesis, showing a significant difference in bow resistance.

It is clear to see the Maier bow created the most resistance at speeds 15, 20 and 25 knots of speed, this was on average almost two and a half times more resistance than the best performing bow (X-BOW®). This is to be expected as the Maier bow is a design used for aesthetics on yachts, thus compromising performance. The Axe bow created the second highest resistance at all speeds. This result is unexpected as the design is used on fast displacement boats such as patrol boats. The longer bow stem will explain the higher resistance caused at lower speeds as there is more volume to push through the water and therefore more drag generated. The vertical bow created the highest resistance at slower speeds, exactly double of the X-BOW®. This is to be expected as vertical bows are used on yachts which are likely to be heeled over when sailing. Similarly, the vertical bow design is used for vessels prioritising cabin space and internal room, therefore de-prioritising performance.

The bulbous bow was one of the best performing bows, especially at high speeds. The bulbous bow is used on large ships such as cargo vessels, which prioritise the efficiency of the vessel over aesthetics and space. This is to reduce emissions to comply with restrictions and lower transport costs, therefore, these results can be expected. The conventional bow performed similar to the bulbous bow. The conventional bow is a universal default bow used on many different types of vessel, as it is the most commonly found and hosts no priorities or compromises; it is expected to have low resistance. The X-BOW® is used on offshore support vessels and in extreme conditions. The X-BOW® created the lowest resistance at all speeds, which compares to the results gathered from previous studies.

According to Damen (2019), Axe bow designs 'exhibit superior motion behaviour and significantly lower resistance through the water'. From looking at the simulation data the axe bow generated the second highest resistance. It is probable that the hull and stern design negatively impacted the vessels resistance, as vessels hosting an axe bow normally incorporate a smaller beam. Because the simulation designs used the same hull on all bow designs, this would explain the difference in results. Another factor to consider is the fact that the research was carried out by the company itself, raising the possibility of bias and therefore unreliability.

Hassan, *et al* (2017) states that the 'X-bow reduces 16%-49% resistance'. In comparison, the data gathered in the current study fully supports Hassan *et al's* (2017) report; as the X-BOW® created the lowest resistance of other bow designs at all speeds. However, the X-BOW® simulations were done with the vessel stationary in the water with a calm sea state. In order to obtain accurate results and support Hassan's report fully, the simulations would need to be conducted in a rough sea state. This is especially important, as the X bow is configured to 'push the ship lower under the waves, rather than riding over the top of them, resulting in huge amounts of spray—and very wet decks' (Mackenzie, 2019).

The report on bulbous bows by Chrismianto, Kiryanto and Adietya (2018) found that Bulbous bows reduce drag and thus increase speed, range, fuel efficiency, and stability. Comparing this to the data collected, the bulbous bow created the second lowest resistance and therefore supports the data research found.

Using a report on flat hull ships by Syahril and Nabawi (2019), showed that the Raked/ Maier bow has the lowest resistance of 314.74 N, followed by the Plumb/Vertical bow at 335.44 N and finally, the Conventional bow. Comparing the data from the research found, it does not support Nabawi's data as the Maier bow created more resistance than the Vertical bow at all speeds. Similarly, the Conventional bow outperformed the Maier and Vertical. The difference in results could be from many factors, Nabawi's report was based on using flat hull ships rather than displacement hulls.

As a computer simulation-based study there are potential threats to validity. Some of these are due to limitations in the program itself, specifically shortcomings in reflecting the actual design procedures in real-world situations. Because the Froude number of the vessels was unchanged and automatically decided by the simulation, it is difficult to ensure the ecological validity of the results: In a real-world scenario hull design would depend on the bow. Although each hull was designed the same and only changed from the bow onward, a lot of bow designs work on the premise of using the hull and stern to reduce resistance created.

Although each design had the same waterline level regarding the hull, bow designs such as the Vertical bow are used on sailing vessels which make headway at a heeled angle, mitigating the reliability of the results. This problem becomes a further issue as shown in the research produced by Jeremy (2015) where small deviations were found in Maxsurf® Resistance.

Examining results and supporting the research hypothesis, X-BOW® design demonstrates advantages over other bow designs, thus could be adopted into military vessel design.

Examining warship design, considerations can be subdivided into factors that increase warfighting capability, avoid enemy damage and technologies that reduce the cost of vessel maintenance (Global Security, 2019). The X-BOW® design reduces spray from green water and icing, thus helping to reduce damage to the vessel, equipment, and crew. It could be argued that this is where an X-BOW® design could revolutionise military vessels, as reducing damage to vital weapon systems is a necessity. As shown from the research above conducted on Maxsurf and from conference papers produced by Mosaad, *et al* (2017) X-BOW® produces improved power efficiency. At high Froude numbers, the reduction of wave making resistance is about 50%. This in turn increases the fuel efficiency and therefore running costs. With ever stricter environmental legislation, the use of X-BOW® technology can help to ensure vessels meet this criteria.

Observing baseline general arrangement drawings for military surface ships, there are some factors that would prevent the X-BOW® use in military vessels. Avoiding detection from enemy sensors, is a key design consideration for military surface ships, 'radar signature is being reduced through appropriate shaping of all warship external surfaces' (Global Security, 2019). However, the X-BOW® is a large design, that would add three decks to the initial architecture, generating a larger target and greater surface area for sensors to reflect, therefore, other inverted bow design types, may still be favourable. As shown on Frances new Frégates de Défense et d'Intervention (FDI) frigate, the inverted bow 'comes with distinct advantages: it reduces the ship's radar signature' (Mackenzie, 2019).

Weapon firing arc arrangements is another major design consideration for military warships. Naval vessels require a wide firing arc to reduce positioning and increase range. The use of a tall X-BOW® would reduce this firing arc, especially in frigates, where the bow is host to a gun-turret. An X-BOW® design would create reduced space on the foredeck, resulting in less armaments in this area. However, as the X-BOW® design provides a larger deck space amidships and aft, these armaments could be repositioned.

Modern naval operations are changing from open-ocean warfare to joint operations, conducted in the littoral battlespace. According to Sinex and Winokur (1993), this battlespace encompasses a complex coastal environment with highly dynamic oceanographic and meteorological processes. The Ulstein X-BOW® is a favourable design in 'rough head seas', as slamming, tortional stresses and vibrations are minimised. If naval operations are moving away from open ocean warfare, the need for this characteristic is reduced.

6. Conclusion

This research has concluded that the X-BOW® design is the most efficient in a calm sea state, thus backing the research hypothesis. The X-BOW® design could provide future avenues for military applications. Continuing with this project, it would be recommended that more time is spent on shaping the designs for testing in Maxsurf Resistance. As stated by Charleston Marine Consulting (no date) 'The only 100% accurate way of determining resistance of a vessel is to build a full-size hull and measure the actual resistance with a tow cable'. Therefore, future research could involve the accurate modelling of the varying bow designs on a designated hull shape to test in a towing tank. This would mitigate any chance of simulation inaccuracies and allow the author to visualise their performance in a real water environment. This future research would help to validate the results and assist naval architects to construct more efficient bow designs. Naval Architects, both military and commercial may decide to advance this project to delve into more efficient designs. This would reduce the power required to thrust ships and therefore reduce the fuel consumption, leading to reduced cost and pollution. These are both very important factors as environmental impact is a key problem and legislation/restrictions are becoming more influential.

Word Count: 4398 words.

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References

Figure 1: Mosaad. M., et al,. 2017. X-bow Design for Ship Energy Saving. *Influence of EEDI on Ship Design & Operation*, 13 September 2017. London, UK. Available from: https://www.researchgate.net/publication/325128735_X-bow_Design_for_Ship_Energy_Saving [Accessed: 13 October 2019].

Figure 2: Global Security., 2019. *Bulbous Bow* [online]. Available from: https://www.globalsecurity.org/military/systems/ship/bulbous-bow.htm [Accessed 13 October 2019].

Figure 3: Datawave Marine Solutions., 2018. *Splitting Waves and Hairs: Comparing X-Bow, Axe Bow, and More* [online]. Available from: https://dmsonline.us/splitting-waves-and-hairs-distinguishing-between-bow-shapes/ [Accessed 13 October 2019].

Figure 4: IMGBIN., 2018. *Patrol Boat Damen Group Ship Coast Guard Axe Bow PNG* [online]. Available from: https://imgbin.com/png/Db7CM52w/patrol-boat-damen-group-ship-coast-guard-axe-bow-png [Accessed 13 October 2019].

Figure 5: Britannica., 2019. *Froude Number* [online]. Available from: https://www.britannica.com/science/Froude-number [Accessed 26 September 2019].

Figure 6-26: Bentley,. 2019. *Maxsurf Modeller* (Version 22.01) [software]. Available from: https://www.bentley.com/en/products/product-line/offshore-structural-analysis-software/maxsurf [Accessed 04 December 2019].

Figure 27-266: Bentley,. 2019. *Maxsurf Resistance* (Version 22.01) [software]. Available from: https://www.bentley.com/en/products/product-line/offshore-structural-analysis-software/maxsurf [Accessed 19 December 2019].

Bentley., 2018. Maxsurf (V21.12.00) [software]. Available from: https://www.bentley.com/en/products/product-line/offshore-structural-analysis-software/maxsurf [Accessed 26 September 2019].

Britannica., 2019. *Froude Number* [online]. Available from: https://www.britannica.com/science/Froude-number [Accessed 26 September 2019].

Charleston Marine Consulting., no date. *Maxsurf Resistance* [online]. Available from: http://charlestonmarineconsulting.com/maxsurf-naval-architecture-software/maxsurf-resistance/ [Accessed 30 October 2019].

Chrismianto. D, Kiryanto and Adietya. B., 2018 Analysis of Effect of Bulbous Bow Shape to Ship Resistance in Catamaran Boat. *MATEC Web of Conferences 159, 02058*. Available from: https://www.matec-conferences.org/articles/matecconf/pdf/2018/18/matecconf_ijcaet-isampe2018_02058.pdf [Accessed 13 October 2019].

Damen., 2019. *Damen takes a bow* [online]. Available from: https://www.damen.com/en/innovation/some-key-projects/sea-axe-design [Accessed 13 October 2019].

Datawave Marine Solutions., 2018. *Splitting Waves and Hairs: Comparing X-Bow, Axe Bow, and More* [online]. Available from: https://dmsonline.us/splitting-waves-and-hairs-distinguishing-between-bow-shapes/ [Accessed 13 October 2019].

Global Security., 2019. *Ship Design* [online]. Available from: https://www.globalsecurity.org/military/systems/ship/design.htm [Accessed 20 April 2020].

Hassan. H., *et al*., 2017. *X-bow Design for Ship Energy Saving*. Thesis (B.SC). Port-said University. Available from: https://www.researchgate.net/publication/325128735_X-bow_Design_for_Ship_Energy_Saving [Accessed 13 October 2019].

Island Computers., no date. *Maxsurf Motions / Motions Advanced* [online]. Available from: https://www.islandcomputers.co.uk/motions.html [Accessed 7 November 2019].

Keuning, J.A., *et al*., 2002. Further Investigation into the Hydrodynamic Performance of the AXE Bow Concept. Available from: https://pdfs.semanticscholar.org/4148/d25ecbddc2d42166c82ef22762f23fedc89e.pdf [Accessed 13 October 2019].

Jeremy, J., 2015. The Australian Naval Architect. *The Royal Institution of Naval Architects (Australian Division)*. Volume 19 Number 2. P. 12. Available from: https://www.rina.org.uk/res/The%20ANA%20Vol%2019%20No%202%20May%2015.pdf [Accessed 7 November 2019].

Liul.Y., *et al*., 2014. Numerical study on effects of buffer bulbous bow structure in collisions. *Recent Advances in Structural Integrity Analysis - Proceedings of the International Congress 2014*. Pages 168-172. Available from: https://www.sciencedirect.com/topics/engineering/bulbous-bow [Accessed 13 October 2019].

Mackenzie, C., 2019. *France's new warship will have an inverted bow and 2.2-ton radar panels* [online]. Available from: https://www.popsci.com/story/technology/french-fdi-frigate-inverted-bow-flat-radar/ [Accessed 04 August 2022].

Maxsurf., 2022. *Maxsurf* [online]. Available from: https://maxsurf.net/ [Accessed 04 August 2022].

Maxsurf., no date. *About Maxsurf* [online]. Available from: https://www.maxsurf.net/aboutmaxsurf.html [Accessed 26 September 2019].

Maxsurf., no date. *Maxsurf and Multiframe brochure screen* [online]. Available from: https://www.maxsurf.net/Maxsurf%20and%20Multiframe%20brochure%20screen.pdf [Accessed 30 October 2019].

Maxsurf., no date. *Maxsurf Resistance* [online]. Available from: https://www.maxsurf.net/resistance.html [Accessed 30 October 2019].

Mosaad, M., *et al*., 2017. On the Design of X-bow for Ship Energy Efficiency. *Influence of EEDI on Ship Design & Operation*. Northumberland Street, London. 13 September. Volume: 1. Available from: https://www.researchgate.net/publication/320311087_On_the_Design_of_X-bow_for_Ship_Energy_Efficiency [Accessed 02 June 2022].

Syahril, S. and Nabawi, R. 2019. Numerical investigation of the effect on four bow designs flat hull ship. *International Journal of GEOMATE*. Vol, 17. Issue 62, pp. 231 – 236. Available from: https://www.researchgate.net/publication/334251711_NUMERICAL_INVESTIGATION_OF_THE_EFFECT_ON_FOUR_BOW_DESIGNS_FLAT_HULL_SHIP [Accessed 13 October 2019].

Sinex, C. and Winokur, R. 1993. Environmental factors affecting military operations in the littoral battlespace. *Johns Hopkins APL Technical Digest*, Volume 14, Number 2. Pp.112. Available from: https://www.jhuapl.edu/content/techdigest/pdf/V14-N02/14-02-Sinex.pdf [Accessed 23 May 2022].

Ulstein., no date. *X-BOW®* [online]. Available from: https://ulstein.com/innovations/x-bow [Accessed 13 October 2019].

Wartsila., 2019. *Bow* [online]. Available from: https://www.wartsila.com/encyclopedia/term/bow [Accessed 23 September 2019].

Yang, K. and Kim, Y. 2016. Numerical analysis of added resistance on blunt ships with different bow shapes in short waves. *Journal of Marine Science and Technology*. Volume 22, Issue 2, pp 245–258. Available from: https://link.springer.com/article/10.1007/s00773-016-0407-9 [Accessed 13 October 2019].

Appendices

A full list of appendices can be found by following the link below:

https://ln5.sync.com/dl/de9b6ce90/i2wuk64a-fwdiweqj-ipe28meh-btgyfwc4