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The Advanced WaterJet: Propulsor Performance and Effect on Ship Design

Will Giles, BEng, MSc, CEng, MRINA
Tom Dinham-Peren, BSc, MRINA
Shane Amaratunga, PhD, CEng, MIMechE
BMT Defence Services Limited, UK
Arthur Vrijdag, MSc, PhD, CEng, MIMarEST
Richard Partridge, MSc, CEng, MIMechE, MIMarEST
Rolls Royce Naval Marine, UK

SYNOPSIS

Future naval platform procurement will continue to be influenced by a combination of innovative design, capability and affordability (both capital and through life). Propeller driven platforms have traditionally dominated larger surface combatant designs due to high efficiencies and system maturity. However, developments in submerged waterjet technology now present a viable alternative for certain classes of ship, and might be particularly attractive to those with anti-submarine warfare roles where underwater acoustics are critical to platform capability. The merits of alternative propulsion systems should be based on whole ship propulsion efficiency, rather than the efficiency of the propulsion system in isolation.

Submerged waterjets offer potential for propulsion system weight and space savings and can be considered a key enabler for full electric propulsion (FEP) on smaller platforms. The benefits in terms of general layout and machinery arrangement could allow alternative uses of space to be considered, e.g. deployment and recovery of off-board systems. The nature of the submerged waterjets offers further benefit with respect to platform underwater acoustic signature. While these are potential benefits, there are uncertainties with respect to the integration and optimisation into the hull form that will affect the overall propulsive efficiency when compared to conventional propeller designs. In particular, hull-propulsor interactions represent an area where particular attention is necessary.

Over the past few years Rolls-Royce has developed a submerged waterjet - the Advanced WaterJet or AWJ-21™. This paper provides an insight into the new developments of the Rolls Royce AWJ-21™ and the wider impact of submerged waterjets on platform design.

Will Giles is a Senior Naval Architect in the Surface Ship Team within the Naval Architecture Department of BMT Defence Services.
Tom Dinham-Peren is the Chief Hydrodynamicist at BMT Defence Services.
Shane Amaratunga is a Senior Principal in the Naval Architecture Department of BMT Defence Services.
Arthur Vrijdag is a propulsion system engineer with Rolls-Royce.
Richard Partridge is the Propulsion System Manager of New Projects with Rolls-Royce.

INTRODUCTION

Rolls Royce Naval Marine (RRNM) has developed an advanced waterjet propulsor (AWJ-21™), which is a candidate system for future surface combatant programmes. While RRNM have carried out considerable development on the design of the propulsor, limited research has been undertaken to explore integration of the system into a concept design.

The introduction of submerged waterjet technology, such as the AWJ-21™, poses some significant challenges and opportunities to whole-ship design:

1) The propulsor itself introduces differing characteristics in terms of geometry, thrust produced, operating speed and signatures;

2) Frigate sized surface combatants are almost exclusively optimised for propellers and, therefore, the impact upon the hullform design criteria will need to be determined to accommodate the AWJ-21™ geometry effectively;
3) The interaction of flow with the hull for waterjets is considerably different to conventional propellers;
4) The entire propulsion train is affected by the choice of propulsor;
5) All the above will have an impact upon the constraints in internal arrangement.

To explore the impact on hullform, a conventional hullform was derived and optimised for propeller propulsion, along with a new, first iteration hullform based on the AWJ-21™ propulsor. CFD analysis was conducted to derive the flow characteristics of each hullform. The propulsive coefficients were obtained and the sensitivity of these coefficients was explored. The power curves for each hullform were then used to assess a full electric propulsion architecture utilising AWJ-21™ and propeller propulsion respectively, thus giving a whole ship propulsion efficiency comparison. Finally, the effect of waterjets on required inboard volume and the resulting opportunities were investigated by developing a different ship layout compared to conventional vessels.

CHARACTERISTICS OF THE AWJ-21™

Geometry

The AWJ-21™ is a conventional waterjet with a completely submerged discharge. The mixed flow pump, outlet and the associated steering/reversing apparatus are mounted in a hydrodynamically faired body termed a “nacelle” that, in conjunction with the intake duct, is integrated with the hull of the ship. The inlet is shaped as to minimise distortion of the inlet flow, while the nacelle is shaped to minimise “nacelle” drag.

The geometry of the AWJ-21™ integrated in a hull is shown in Figure 1, with the schematic layout shown in Figure 2. The layout of the aft end of the vessel depends on the type of AWJ-21™ (boost, boost-reversible or steerable/reversible). The hydraulic actuator that is used for steering and reversing is mounted inside the hull. Steering is possible by rotating the outlet nozzle and, thereby, deflecting the outlet jet sideways so that no rudders or large conventional steering gear are required. The connection between the actuator and the steering nozzle is fully integrated in the nacelle. Reversing takes place by mechanically altering the outlet flow direction using a reversing bucket combined with an outlet flap that is integrated in the bottom of the nacelle.

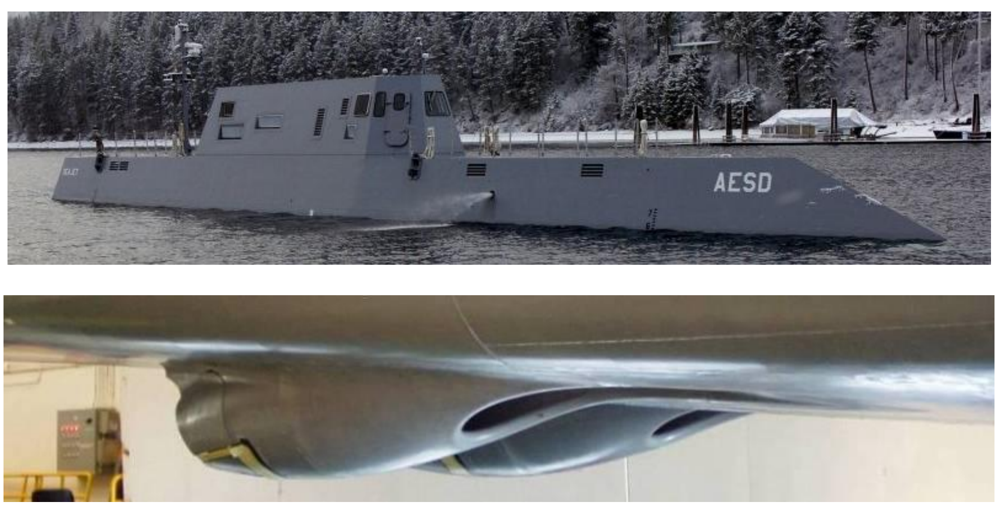

Figure 1: Advanced Electric Ship Demonstrator (AESD) with AWJ-21™ Technology

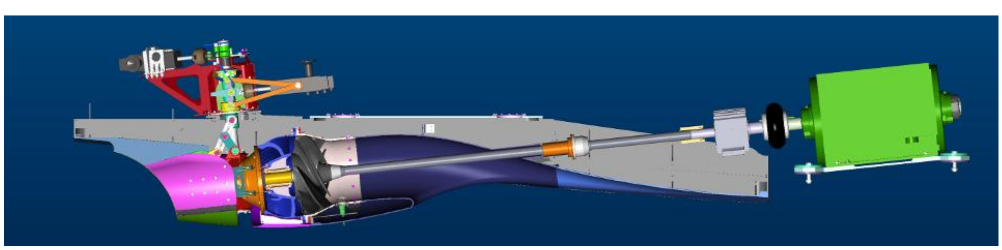

Figure 2: Schematic Layout of the AWJ-21™

The AWJ-21™ has been tested at model scale and has also been evaluated by the US Navy on the "Advanced Electric Ship Demonstrator" (AESD). The AESD has a length of 133ft (41m) and is powered by either a small diesel generator set or batteries. The batteries eliminate the diesel as a noise source for quiet and high-speed tests operations.

Propulsor Sizes

The associated dimensions, mass and operating speeds of AWJ-21™ are listed in Table I and geometry detailed in Figure 3.

Unit designation (Std. Decimal Geometric Series R15)	Propulsor Inlet Diameter (CM)	Est-Propulsor Mounting Flange Diameter at Submerged Transom (CM)	Indicative Range of Installed Brake Power/Propulsor (KW)		Indicative Range of Propulsor Operating Speeds (RPM)		Approx Propulsor Length Aft of Mounting Flange (CM)	Approx. Inlet Length Fwd of Mounting Flange to Stern Tube Shaft Seal Mount (CM)	Est- Steering & Reversing Unit Mass (KG)	Est-Boost propulsor Dry Mass (KG)	Est-Inlet & Nacelle Mass (KG)	Est-Entrained Water Mass (KG)
-SR, -B, -RB[0]	D_{INLET}[1]	D_{MOUNT}[2]	Min	Max	Min[3]	Max[3]	L_{OUTBD}[4]	L_{INLET}[5]	M_{BR}[6]	M_{B}[7]	M_{IN}[8]	M_{BW}[9]
AW J21-58	58	90	1100	1700	1030	1220	145	232	400	700	500	200
AW J21-68	68	106	1400	2400	880	1040	170	272	700	1100	700	400
AW J21-80	80	124	2000	3200	750	880	200	320	1000	1800	1000	600
AW J21-94	94	146	2700	4500	630	750	235	376	1600	2800	1400	900
AW J21-110	110	171	3700	6100	540	640	275	440	2500	4300	1800	1400
AW J21-129	129	200	5000	8400	460	550	323	516	3800	6600	2500	2200
AW J21-151	151	234	6900	11500	390	470	378	604	5900	10300	3400	3500
AW J21-177	177	275	9400	15700	330	400	443	708	9100	16000	4700	5600
AW J21-207	207	321	12900	21500	290	340	518	828	14100	24700	6400	9000
AW J21-242	242	376	17600	29300	240	300	605	968	21900	38300	8800	14300
AW J21-283	283	439	24100	40100	210	250	708	1132	33900	59300	12000	22900

[0] SR-Steering/Reversible, B-Boost, RB-Reversible/Boost
[1] Custom Intermediate sizes as required
[2] Estimate based on mixed flow pump, axial flow pump - 10-15% smaller
[3] Over range of installed powers
[4] Assumes integral Steering/Reversing. Boost only configurations 30-40% shorter
[5] Typical (+/- 10%) actual length may be longer/shorter depending on integration
[6] Includes pump components. Drive shaft outboard steering/reversing hardware - does not include Inlet, nacelle, or inboard actuation system weight
[7] Includes pump components. Drive shaft - does not include Inlet, nacelle, outboard steering/reversing hardware or inboard actuation system weight
[8] Steel construction assumed aluminium or fibreglass/composite may be less
[9] Entrained sea water is Inlet & pump less added buoyancy from nacelle

Table I: Particulars of the AWJ-21™ Range

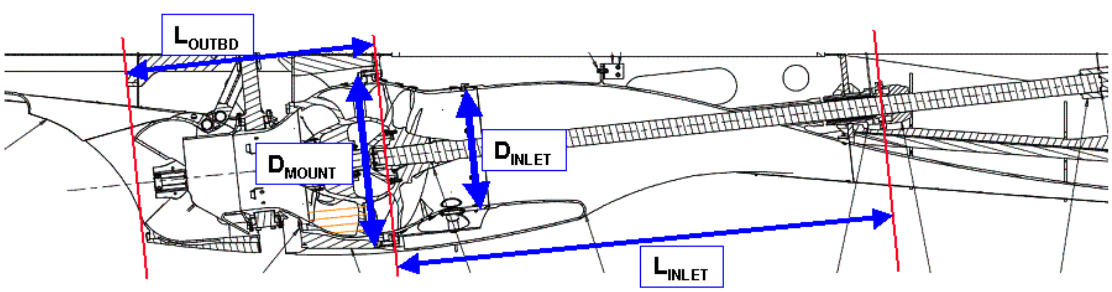

Figure 3: Length Definitions

Signatures - Underwater Noise

Underwater noise is an important consideration for naval ship design, particularly with respect to ASW and mine hunting operations. Cavitation is a major contributor to the underwater acoustic signature; although no full scale AWJ-21™ underwater noise data is presented here for reasons of confidentiality, some qualitative remarks on underwater noise can be made.

For both propeller and waterjet driven ships, discrete tones in the lower frequency band related to machinery (diesels and gearboxes) are dominant. For electric propulsion, the underwater acoustic signature caused by drives and electric motors is highly dependant on the characteristics of these specific subsystems. Hence, irrespective of the propulsor, the underwater noise at these frequencies is dependent on the type and mounting of the equipment.

For a propeller driven ship, the pre-cavitation noise intensity level in the medium and high frequency range reduces towards the lower end of the spectrum. With increasing ship speed, beyond the inception point, a pronounced broadband “hump” arises in the higher frequencies. This hump is caused by propeller cavitation and, with increasing cavitation intensity, becomes more pronounced and shifts to lower frequencies. Beyond the inception point, the noise level due to cavitation very quickly surpasses the machinery noise and, hence, it can be said that propeller cavitation is almost always the dominant contributor to the acoustic underwater signature.

The noise generated by a conventional waterjet can have various sources:

1) The WJ inlet- If not carefully designed the inlet lip (where the inlet starts) can start to cavitate early, although with a good design this can be delayed up to 44 knots (Reference 1);
2) The pump itself;
3) Discharge on the water surface.

The adoption of a submerged waterjet will significantly impact aspects 1 and 3. The AWJ-21™ pump design benefits from many years of experience in conventional waterjet development within Rolls-Royce, as well as increased head due to the submerged location. Based on these considerations it is very plausible that the AWJ-21™ offers improved underwater signature compared to propeller driven or conventional waterjet driven ships.

HULLFORM DEVELOPMENT AND RESISTANCE ESTIMATES

To conduct a fair comparison of AWJ-21™ technology as a propulsion option against a conventional propeller, the interaction between the hull and propulsor must be incorporated (Reference 2 and 3). The hull influences waterjet inflow due to the hull boundary layer while at the same time the presence of the waterjet influences the flow over the hull, which affects the velocity and pressure distribution over the hull (and thus ship resistance). Local geometry changes and differences in appendages should also be incorporated.

The baseline concept design is a conventional displacement monohull as outlined in Table II and represents a typical modern frigate-sized vessel. The hullform is based on parent hullforms exhibiting favourable resistance characteristics and includes a twin screw stern arrangement with open shafts, twin rudders and one set of A-Brackets per shaft.

Length between Perpendiculars	130m
Beam moulded	16.5m
Draught	5.7m
Speed	30knots
Displacement	6500Te

Table II: Hullform Parameters

The AWJ-21™ hullform was developed based on the conventional hullform. Modifications included slight tunnelling of the stern aft and widening of the hull to provide a suitable location for the waterjet to be fitted. Part of the object in placing a ‘soft’ tunnel on the naked hull was to provide a beneficial environment for the waterjet to operate in, the purpose being to draw the boundary layer towards the waterjet intake and to provide a local static pressure rise.

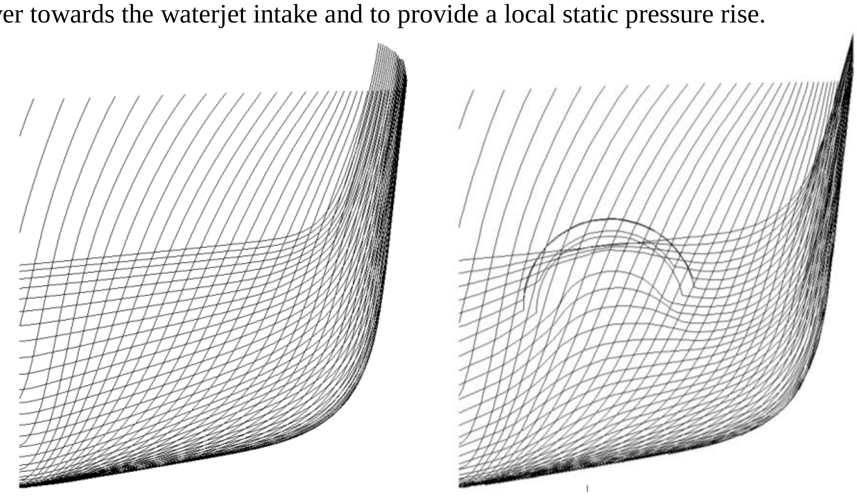

Figure 4: Conventional Hullform & AWJ-21™ Hullform Lines Plan

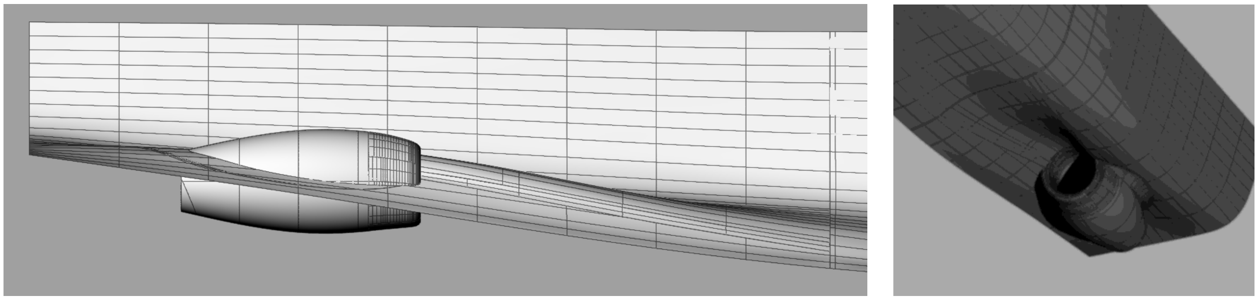

Figure 5: AWJ-21™ Hullform and Propulsor

The CFD software package CFX was used to derive a resistance curve and to give some insight into the propeller hull interaction factors. The propulsors were modelled as momentum sources with the values of thrust and torque set for each speed. The radial distribution of the axial and rotational momentum on the actuator disc was determined to match the distribution as given in Reference 4.

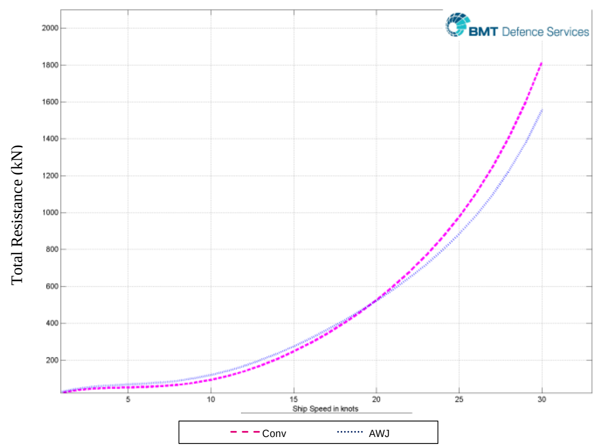

Figure 6: Resistance Curves including respective appendages

The total resistance of the two vessels vary as shown in Figure 6. The AWJ-21™ hullform exhibits a slightly lower resistance at higher speeds but comparable resistance at 18knots. This is considered to be due to the advantageous effects of the tunnel hullform design of the AWJ-21™ hullform, and is in accordance with recent model tests in which tunnel hulls have exhibited favourable resistances at higher speeds.

POWERING ESTIMATES

The propulsive coefficients form the link between the effective power calculated above and the delivered power from the engine to the propulsor. Calculation of the propulsive coefficients has traditionally been difficult due to the complexities of hull-propulsor interactions. While considerable analysis has been carried out to predict propulsive coefficients for conventional propulsors (model tests and empirical analysis), little has been carried out for AWJ-21™ technology. In order to assess the sensitivity of propulsive calculations in this study, two delivered power calculations were carried out for the AWJ-21™:

1) An empirical method was conducted, based on conventional waterjet theory which was adapted for a submerged design using the first principles methodology developed by van Terwisga, see Reference 3; Calculations were carried out using the BMT proprietary software tool Ptool, which is a marine power and propulsion assessment tool (Reference 5 and 6).
2) A “momentum flux” method as recommended by the ITTC (References 7 and 8), involving the analysis of the flow through control planes, incorporating the performance characteristics of the waterjet, the inlet and discharge losses and the interaction between the waterjet and the hull.

A propulsion prediction for the conventional propulsion form was obtained based on a regression analysis using appendage allowance, wake fraction, thrust deduction and relative rotative efficiency estimated from past data. This estimate was further refined using Ptool. Table III details the propeller characteristics used in both methods.

No. Blades	5
Diameter	4.3m
P/D	1.203
Blade Area Ratio	0.95

Table III: Propeller Dimensions

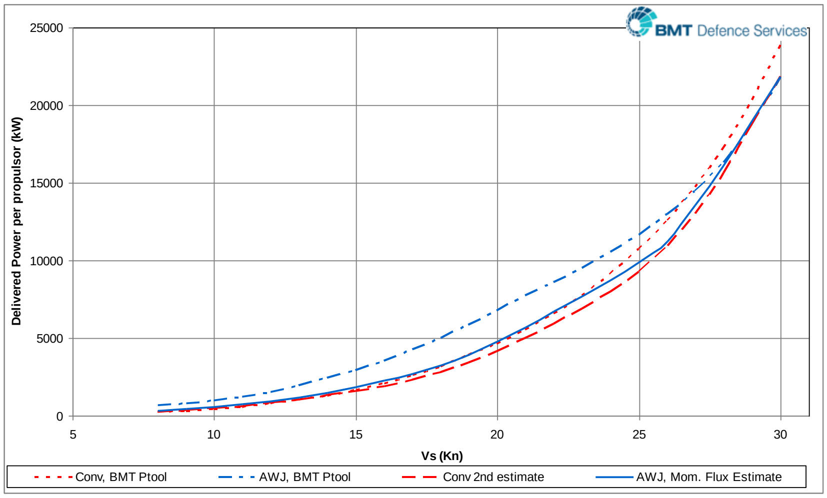

Figure 7: Delivered Power Curves

Figure 7 shows the variance in calculated delivered power. The conventional propulsion results display a similar increase in delivered power with increasing speed. The AWJ-21™ initial calculation using the momentum flux method, however, displays considerably different results to the Ptool method. Delivered power in the low to mid-speed range is higher than that of the Ptool method, and convergence occurs at speeds greater than approximately 28 knots. The figure also suggests that AWJ-21™ technology could become more efficient than a conventional propeller at speeds above approximately 24 to 26 knots. These powering calculations demonstrate the sensitivity to propulsive coefficients and illustrate the need for further research to develop a robust and mature calculation procedure for AWJ-21™ technology.

Discussion on Momentum Flux Power Results

A comparison between the total shaft powers using the momentum flux method is presented as (Ps/Vs^3) to make the relative difference in power levels through the speed range clearer. At 18 knots the AWJ-21™ form has 15% higher power requirement, but at 30 knots the power is comparable. At speeds higher than 30 knots the AWJ-21™ form is expected to be better than the propeller hullform.

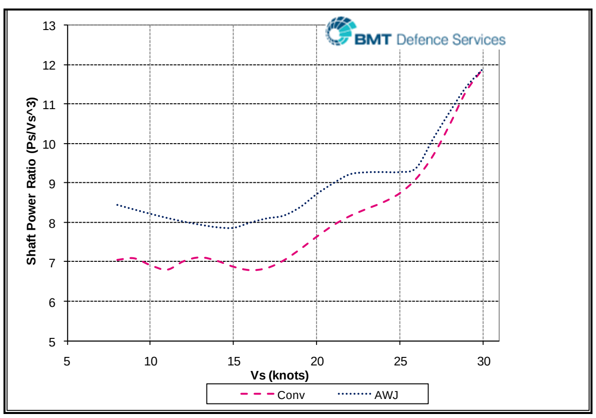

Figure 8: Comparison of Shaft Power

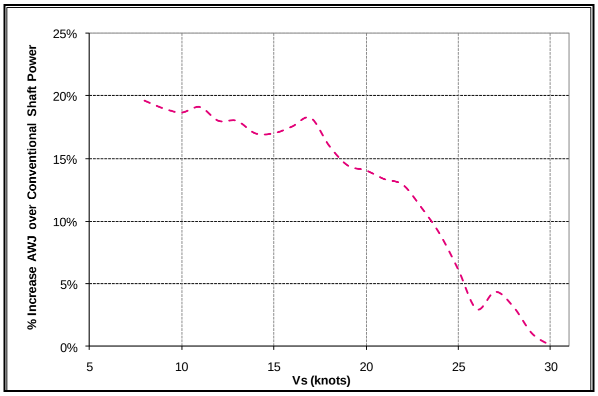

Figure 9: Increase in Power for AWJ-21™ Vessel over Conventional Vessel

This is an encouraging result for a first iteration as the AWJ-21™ arrangement has not been fully optimised and, hence, there is further prospect of reducing the shaft power for this form. If the power could be reduced by 5% (e.g. by further improving the waterjet/hull fairing), then the AWJ-21™ vessel would be better at all speeds above 25 knots.

PROPULSION ANALYSIS

To undertake the propulsion selection for both propeller and AWJ-21™ architectures, the empirical Ptool method of calculating power was employed in favour of the momentum flux method. This approach represents the largest difference between propeller and AWJ-21™ powers and, as such, the derived differences represent a pessimistic assessment. It is the intention to conduct a similar propulsive selection with the momentum flux method in due course.

Each design was tailored to suit the propulsor fit and the sizing of the electric propulsion motors (EPM) and engine fit was matched to the needs of the whole power and propulsion system. All propulsor options were driven by electric motors, thus the benefits of full electric propulsion were realised in both designs. The propulsion analysis resulted in the following power requirements:

1) AWJ-21™ architecture- 1 Rolls-Royce MT30 gas turbine rated at 36MW @ 3600rpm + 3 Bergen B32:40V16P engines rated at 8MW @ 750rpm each;
2) Conventional architecture- 1 Rolls-Royce MT30 gas turbine rated at 36MW @ 3600rpm + 4 Bergen B32:40V16P engines rated at 8MW @ 750rpm each.

The ship's electrical demand was assumed to be 2300kW when cruising at all speeds. The additional generator was specified for the propeller architecture due to a larger delivered power requirement at the maximum design speed (30 knots), see Figure 7.

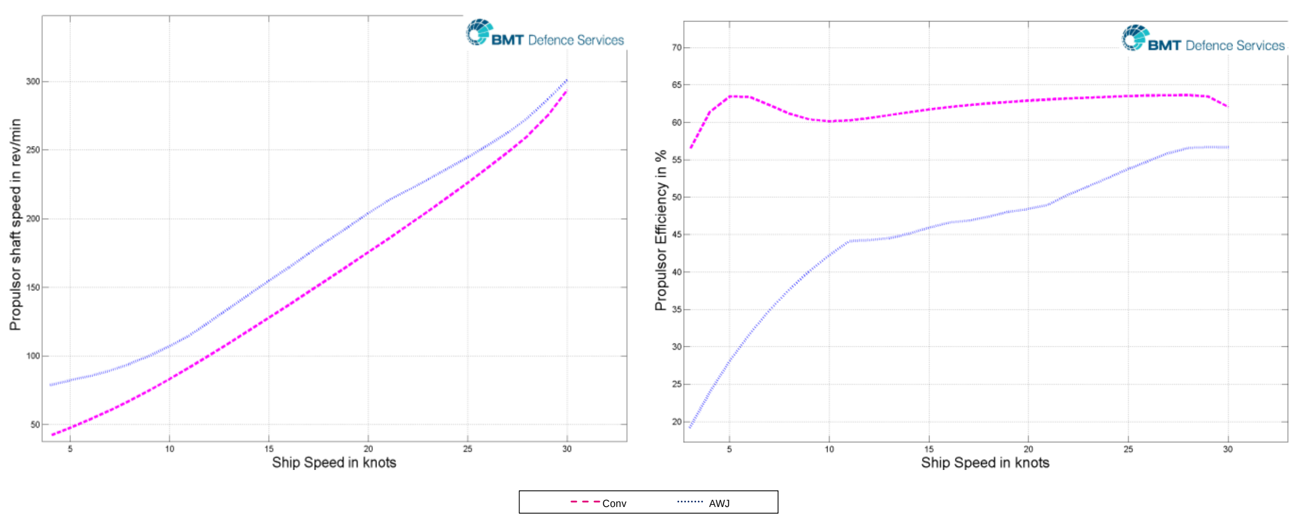

Figure 10: Propeller Shaft Speed and Efficiency

Figure 10 shows the rpm at all speeds is higher, resulting in less torque for the AWJ-21™. Since torque is a main driver for electric motor diameter, a smaller motor is required.

The power and propulsion machinery study has shown that the AWJ-21™ design allows for a smaller machinery fit. In order to quantify the likely savings, the following estimated sizes have been calculated.

	EPM		Machinery Differences	
	Weight	Volume	Weight	Volume
	Tonne	m^2	Tonne	m^2
Conventional Architecture	93	82	2,447	6,152
AWJ-21™ Architecture	66	70	2,126	5,193
Difference (As % of Conventional)	-29%	-15%	-13%	-16%

Table IV: Propulsion Sizes

Table IV suggests a reduction in required machinery for AWJ-21™ technology; this is primarily due to the smaller number of required gen-sets. The relative merits of the reduction in volume are discussed later.

A larger propeller specification leads to lower rpm and higher torque, resulting in a larger motor, thus increasing machinery size and also, therefore, the advantage of AWJ-21™ technology. In order to quantify this affect, a 5m propeller was considered. This resulted in a motor size increase of approximately $10m^3$ (6%), which was considered small for this level of maturity. Therefore, the 4.3m propeller was maintained for this analysis.

Fuel Requirements

A time-based operating profile of the ship was estimated in order to derive an approximation for fuel capacity. This is shown in Figure 11:

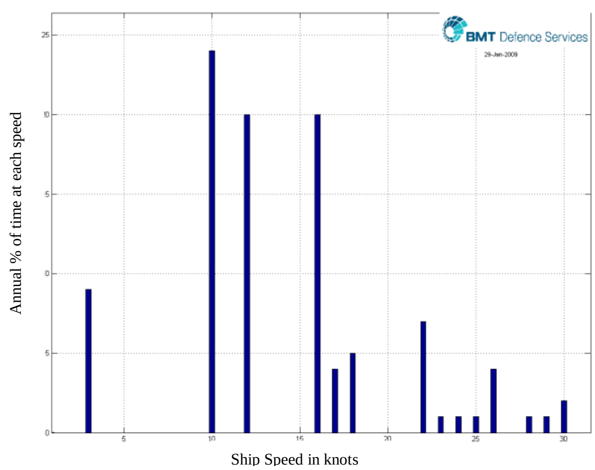

Figure 11: Assumed Operating Profile

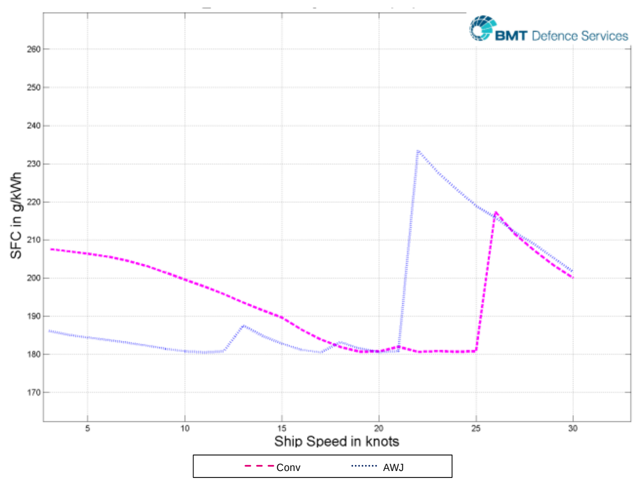

Figure 12: Specific Fuel Consumption

Figure 12 details the specific fuel consumption (SFC) across the speed range. At lower speeds the diesel generators are less loaded in the propeller arrangement resulting in a worse SFC than the AWJ-21™ arrangement. It can clearly be seen that the turbine is needed by the AWJ-21™ at a lower speed; this is due to the variation of propulsor efficiency across the speed range. However, at a cruise speed of 18 knots, there is little difference in specific fuel consumption between the two architectures.

The AWJ-21™ propulsion requires approximately 250 tonnes more fuel. However, there is a smaller volumetric demand for machinery spaces resulting in a net space saving in the region of 660m^3. A benefit may be realised as fuel tanks offer more flexibility in lay-out and this may also become important as more stringent environmental legislation is imposed and fuel storage may no longer be permitted adjacent to the hull. Hence, trading machinery volume above the inner bottom for fuel storage volume may be advantageous.

The above discussion is encouraging. It is known that waterjet technology is beneficial at higher speeds and not as efficient at lower speeds. The above propulsion analysis shows that while there is a performance penalty in the mid-speed range, overall AWJ-21™ propulsion is comparable to propeller propulsion arrangements. It is, therefore, considered that if AWJ-21™ technology is an enabler in other areas, the penalty associated with propulsive performance could be seen as worthwhile and acceptable.

SHIP INTEGRATION

Integration of the AWJ-21™s into a design poses some interesting issues which need to be explored and understood.

Principal Particulars

Length is a primary cost driver for most ships, and naval ships are no exception. A frigate's length is driven typically by topside systems and integration of these systems (flight deck, hangar, combat systems etc) into a single platform rather than hull volume that is required. Although such factors as uptakes / downtakes and bulkhead spacing for prime movers will influence topside design, the choice of propulsion train is not a primary driver. As such, submerged waterjet technology will not provide significant benefit in reducing ship length. However, an indirect advantage can be realised on smaller ships where choice of propulsion configuration becomes the ship size driver. Adoption of full electric propulsion machinery with a conventional propeller requires large, heavy machinery, a significant proportion being related to the motors due to the low rpm required by the propeller to attain maximum efficiency. AWJ-21™ technology, however, operates at a higher rpm and as such a smaller motor can be utilised. Therefore, the reduction in motor size and equipment associated with AWJ-21™ technology is an enabler to full electric propulsion in smaller platforms.

Stern Design and the Effect on Propulsion Train

Modern frigates incorporate a transom stern with a small amount of immersion. At higher speeds the transom runs dry, thus increasing the effective length of the hullform resulting in a reduction in resistance. There is also a trend towards wider aft forms to create additional volume which can be utilised for deploying equipment from the transom and to create wider flight decks.

In order to accommodate the propeller radius as well as optimal tip clearances with the hull, the shaft line will need to adopt a reasonably high rake angle. Even with such shaft rake, the up-cut of the hullform will still result in the motors being located further forward to remain within the hull lines. This leads to a long shaft length, potentially resulting in shaft whipping under shock loads which could reduce survivability. It also reduces flexibility in arrangement to ensure survivability by limiting the practical separation which may be achieved between propulsion equipments.

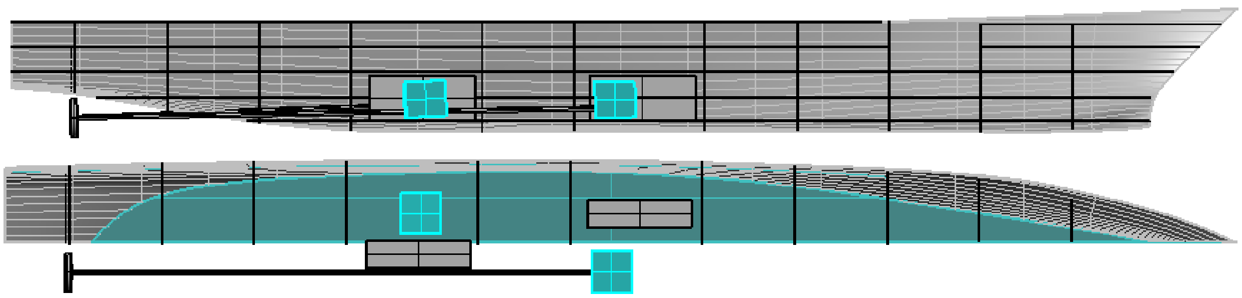

Figure 13: Conventional Machinery Layout

Motor seat height above base	1.2m
Shaft rake angle	3 Deg
Propeller-hull clearance	1m
Min shaft length	37.5m

Table V Propeller Shaft Line Characteristics

The AWJ-21™ is smaller and can be partially integrated into the hullform. This raises the shaft line end point resulting in no shaft rake angle being required and allows the motor to be located further aft. This is further aided by the smaller motor dimensions.

In this example the motors have been located over 1 metre higher compared to the propeller solution and this has reduced the shaft length by up to 15 metres. A second compartment between engine rooms has also been incorporated, thus improving the survivability of the vessel.

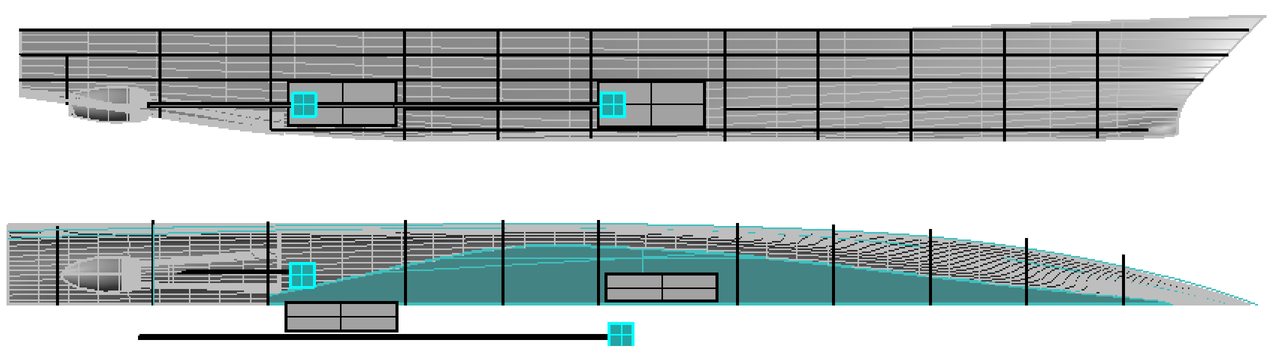

Figure 14: AWJ-21™ Machinery Layout

Motor seat height above base	2.64m
Shaft angle	0 Deg
Propeller-hull clearance	NA
Min shaft length	22.5m

Table VI AWJ-21™ Shaft Line Characteristics

This generates a larger design space and greater flexibility for the Naval Architect to locate the main machinery and other critical items (accommodation, fuel, office space etc) in areas which are otherwise not possible, potentially allowing for a more efficient design.

Shorter shafts could lead to a number of other advantages:
1) Reduced whipping;
2) Reduced material costs;
3) Reduced complexity due to less penetrations through watertight bulkheads (seals, glands, etc);
4) Simpler installation and through-life maintenance;
5) Less mass;
6) Fewer bulkhead penetrations;
7) Fewer bearings.

A further advantage of AWJ-21™ technology be realised in the littoral environment where draught plays a critical role. Conventional propellers protrude beneath the keel, leading to the risk of grounding, propeller damage and possible loss of propulsion. The AWJ-21™, however, is located much higher in the hull (see Figure 14) and is thus geometrically more suited to the littoral environment.

Steering Gear compartment

The steering and reversing machinery associated with the AWJ-21™ results in considerably less volume required at the stern. This allows greater flexibility in the use of this space for other applications, such as a launch and recovery for off-board systems. Figure 15 shows a stern ramp incorporated into the design, which would normally prove difficult due to the presence of large steering machinery in a conventional arrangement. This would require the ramp to be arranged sufficiency high to clear the steering gear compartment, resulting in a potential conflict with the flight deck due to the clearances required above the ramp to embark a boat(s).

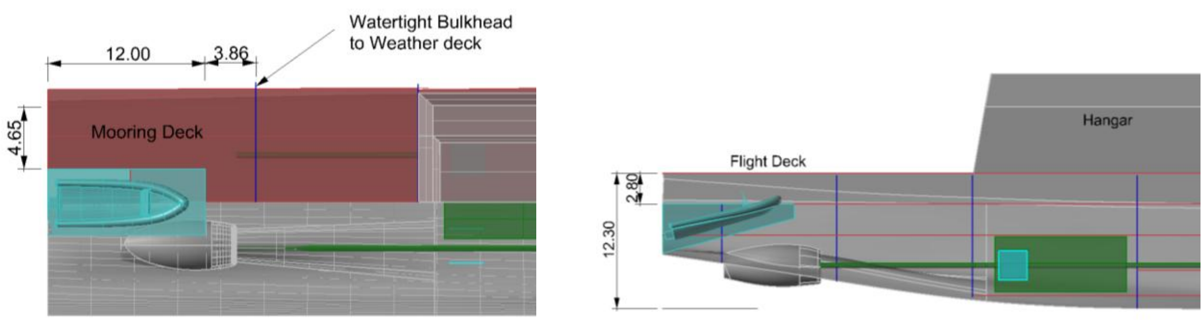

Figure 15: Stern Ramp Integration

Candidate Frigate Design with Principal Features

An initial concept design of a candidate frigate design was produced by collating all the above discussion points (see Figure 16) and incorporating them into a concept featuring AWJ-21™ technology.

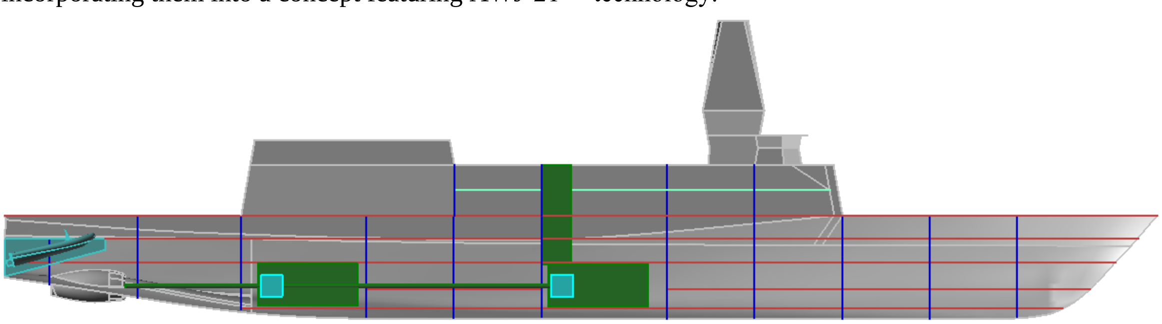

Figure 16: Frigate Concept (Side Elevation)

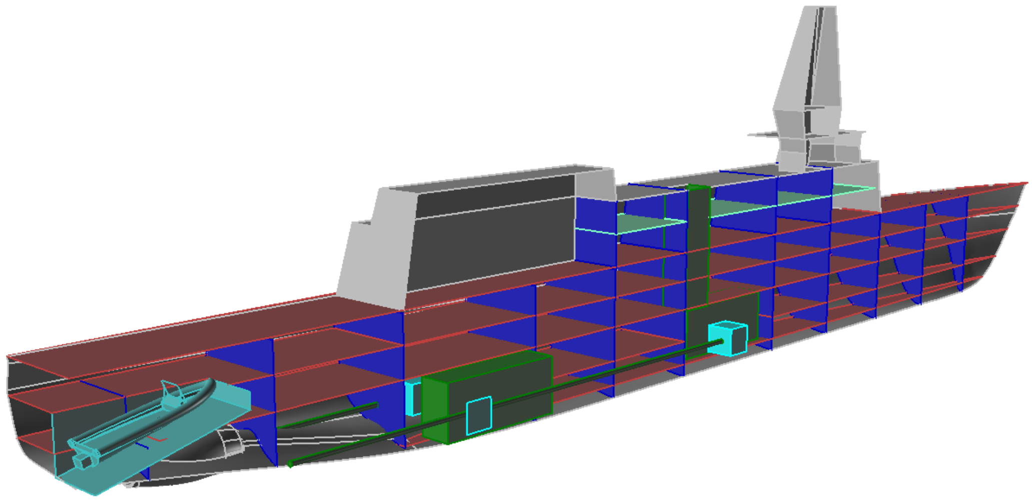

Figure 17: Frigate Cut Away

From the above discussions it can be concluded that AWJ-21™ technology gives the Naval Architect greater freedom and scope in the whole-ship design to produce a design that best suits the application of the platform. This could include locating critical compartments and equipments in optimal positions which may not be feasible with conventional propulsion arrangements.

CONCLUSION

The aim of this paper was to investigate the issues surrounding integration of submerged waterjet technology into a frigate concept and to explore the merits of this technology on whole-ship design, including hullform, propulsion system architecture and ship arrangement.

A conventional propeller hullform and a hullform configured for the AWJ-21™ were developed and the resistance of each form was calculated using CFD. The analyses showed that the resistance of the AWJ-21™ hull was comparable to that of the conventional propeller hullform at lower speeds, and with up to approximately 10% lower resistance at maximum speed (30 knots).

The powering performance of the AWJ-21™ hullform was assessed using two approaches; an empirical method based on conventional waterjet theory and a momentum flux technique recommended by ITTC. Notable differences between the two methods were observed in the AWJ-21™ delivered power calculation, with the empirical method giving a higher prediction then the momentum flux technique in the low to medium speed range due to higher estimated propulsive coefficients. The conventionally propelled hullform performance was derived from empirical estimates, with reasonably similar predictions throughout the speed range. The sensitivity study into the calculation of propulsive coefficients highlighted the need for further research to define a robust and mature calculation procedure for AWJ-21™ technology.

The AWJ-21™ design presented in this paper was not fully optimised due to the relative maturity of the system compared to the well understood propeller. If the AWJ-21™ power requirement could be reduced by some 5%, then this vessel would have a lower power requirement for all speeds above 25 knots.

While the performance penalty at lower speeds was noted, it was shown that AWJ-21™ propulsion was generally comparable to conventional propeller propulsion arrangements at high speed. A lower power requirement at maximum speed will require less installed power and, therefore, less propulsion machinery. Fuel consumption over a typical operating profile is comparable with conventional hullforms.

The potential for AWJ-21™ to significantly change the noise characteristics of the propulsor has an impact on the limitations for current surface combatants where the onset of cavitation above a certain speed dominates the vessels underwater acoustic signature.

Smaller propulsion motors allow greater flexibility to the designer to locate the motors more efficiently and with less impact on the general arrangement. Smaller motors also act as an enabler for full electric propulsion in smaller ships. The integrated manoeuvring capability further reduces the required volume for steering gear, enabling the aft region of the ship to be used in more efficient ways.

It can, therefore, be concluded that submerged waterjet technology does introduce some advantages to the design of a warship, whilst the resulting impact on propulsive efficiency requires further analysis in order to understand if the relative efficiency gap between propellers and submerged waterjets could be closed further.

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