CONSIDERATIONS IN THE SELECTION OF PROPULSION SYSTEMS FOR FAST NAVAL SHIPS

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ABSTRACT

This paper considers the technologies and propulsion products appropriate for ships operating beyond the main resistance hump. Whilst many inshore craft have operated in this regime for many years, increased interest in larger, fast naval vessels has developed in the past few years both in fast logistics and now in fast combatants. Many commercial ferries operate regularly above the main resistance hump. Initially this was implemented with high-speed diesel powered aluminium catamarans, then with larger gas turbine powered monohulls and in the near future with stabilised monohulls or trimarans. Surface Effect Ships have appeared in the passenger market but only infrequently and usually at very high speeds. Recently the USA has acquired fast commercial craft for naval use and some Scandinavian countries have embarked on a build programme for small fast littoral craft. New classes of Fast Attack Craft, larger and faster Corvettes and large ocean-going fast littoral combatants are now either in design or in active consideration by many navies. A greater variety of hull forms are used for fast naval craft than for the more conventional frigates or destroyers. Systems and equipments applicable to Mono-hulls, Multi-hulls (both catamarans and stabilised-monohulls) and Surface Effect Ships are all considered in the context of a propulsion system that suits the particular hull forms. Prime-movers (gas turbines and high-speed diesels), transmissions (electric and geared), and propulsors (propellers and waterjets) are reviewed in relation to the current available technology and the near future anticipated capabilities. Experience gained with existing fast combatants and with respect to the designs for future propulsion system configurations is also described.

INTRODUCTION

Whilst during the early part of the twentieth century naval ships generally exceeded the speed of commercial ships by the end of the twentieth century many commercial ferries were operating regularly at or above 35 knots. Speed was pursued by many navies and adopted innovative hullforms such as hydrofoils and hovercraft however the very expensive lightweight-construction aero-technology and limited payload and range meant these craft were not universally adopted.

New technologies and developments meant that the century closed with high-speed diesel powered aluminium catamarans and larger gas-turbine powered monohulls dominating most world-wide fast transport. Inevitably many navies raised an interest in fast technologies and platforms but conventional bluewater naval strategies found little need or use for speed.

Recently, however, the USA has acquired fast commercial craft and some Scandinavian countries have embarked on a build programme for small fast littoral craft. Experience with these craft has been sufficient for consideration to be given to a new generic class of larger fast littoral combat craft operating at high ship-speeds (Figure 1). These craft present quite a significant challenge to the propulsion system designer.

Figure 1 Operating Speeds for Naval Ships
1. EXPERIENCE WITH CURRENT SMALL FAST COMBATANTS

During the 1960s and 1970s, small naval Fast Attack Craft were developed in a variety of different hull forms including hydrofoils and hovercraft. Many of these were driven by the ubiquitous Rolls-Royce Proteus gas turbine [1]. Over 270 of these 3.7MW units were sold to the marine market. However ship size and speed were held back both by the available power plant and by the ability to transmit the power into the water.

Renewed progress with very fast naval craft has been made recently with the development of two new classes of vessel – Skjold and Visby. Both are of carbon fibre composite construction with Skjold being an SES and Visby a fast monohull. Significantly both have adopted waterjet propulsors and both have adopted gas turbines. To some extent then Naval trends are now following commercial practice of waterjets and Gas Turbines in fast craft.

The prototype Skjold uses a Rolls-Royce propulsion system consisting of a Rolls-Royce Allison 571 gas turbine delivering 5.7MW in a unit weighing only 835 kg. It is coupled to a Rolls-Royce Kamewa size 63 SII waterjet driven through a lightweight Rolls-Royce Allen CODOG Gearbox. For off-cushion loiter operation, power is provided by a MTU 300kW high-speed diesel whilst the 50 knots plus maximum speed is delivered by the gas turbine. This very lightweight propulsion system is ideally suited to the two principal naval operating regimes of loiter and sprint.

The Visby class is a larger ship and produces 16MW from four gas turbines coupled to two low-signature Rolls-Royce Kamewa waterjets (size 125 SII-LM) through a Rolls-Royce Allen combining CODOG gearbox. Gas Turbines provide power for speeds well in excess of 35 knots; with low-speed operation provided by two high-speed diesels of about 1.4MW each for loiter speeds of about 15 knots. The SII-LM waterjets provide unique benefits that include low noise and low magnetic-signature having been specifically designed for fast littoral craft.

Lightweight, fuel-efficient power plants are an essential requirement for these larger and faster craft than was the case for earlier vessels powered by Proteus. These newer craft, as well as the more conventional propeller-driven diesel-powered Fast Attack Craft, are all ‘single-deck’ ships and all operate beyond the main hump speed (Fn~0.54) which for a ship less than 80m waterline length is below 30 knots. Interest is returning in large Fast Attack Craft or small Corvettes at around 60 – 80m and exceeding 35 knots for which a lightweight quad GT CODOG system delivering around 16-24MW are well suited. Figure 2 illustrates a smaller fast littoral craft propulsion system.

2. HULL-FORMS FOR FAST LITTORAL COMBATANTS

Each of the variety of potential hull forms being considered for fast littoral craft poses different challenges for the propulsion system designer. Hull forms promoted for fast craft include semi-displacement monohulls, stabilised monohulls (trimarans), and Surface Effect Ships (SES). These are the three types of craft initially selected for the prototype US Littoral Combat Ship. The two prototype craft for LCS finally chosen and for which prototypes will be being built were a steel monohull and an aluminium trimaran with both craft around 2500t with maximum speed between 40 and 50 knots [2].

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Figure 2 – Small fast littoral craft propulsion system

Figure 3 - Typical power speed curves for fast craft
forms for fighting ships is difficult because the equivalence criteria are so difficult to define.

Payload, deadweight, range, speed, deck area, upper-deck length, radar height and aviation capability are all criteria important to combat ships and which may contribute different selection weightings to different candidate hulls configurations.

Slender semi-displacement monohulls exhibit similar resistance figures to stabilised monohulls albeit the greater wetted surface area of the multi-hull causes higher resistance at lower speeds. Once over the main hump, which the shorter monohulls reach first, wave-making resistance coefficient reduces with increasing speed. Although the monohull drag may be as much as 30% or so worse at the peak of its main hump, further speed increases narrow this difference until again the trimaran has a higher power requirement. SESs are a different order with the lift from the air cushion ensuring low propulsive power but this has to be balanced with a considerable lift-fan power requirement.

In addition to powering requirements, availability of space for the propulsion systems is at a premium in all of the fast hull forms considered. Particularly important issues are weight of the whole system, transom width, and (main) hull space.

### 3. POWER TRANSMISSION

For the new large fast craft, Integrated Full Electric Propulsion IFEP is not feasible with current or near-term electric technology. Size, weight, heat rejection, and transmission efficiency all play against this type of transmission [5]. Yet many of the drivers for such a propulsion system remain, in particular IFEP is a key enabler for future electric mission-systems. Hybrid mechanical/electrical systems may fulfil this requirement to some extent but at this moment in time fast littoral combatants designers are opting for mechanically geared transmission.

### 4. GAS TURBINES

The propulsion power required by the new designs of large Fast Combatants of 2,000 to 3,000t is between 50 and 80 MW and the power density requirements are thus correspondingly extreme. This new class of ships will demand a very high power and extreme compactness. The Rolls-Royce MT30 is a recently marinised version of the new volume-produced aero Trent 800 powering the 777 aircraft. This engine was the first to be approved for twin-engine over-water operation and the engine marinisation has sought to retain, and indeed maximise, this inherent engine reliability.

Commencing marinisation in year 2000, the marine gas turbine MT30 has now achieved DNV certification and has completed its US Navy (ABS) test schedule ahead of its installation in the Integrated Power System (IPS) Engineering Development Model (EDM) for the US Navy’s DD(X) multi-mission destroyer programme. The UK has included this engine in its new aircraft carrier design and MT30 has also been selected for the Lockheed Martin Littoral Combat Ship. MT30 is illustrated in Figure 4.

**Fig 4** Marine packaged 36MW MT30

In its navy configuration, MT30 delivers 36MW at 100°F (38 °C) – the ‘standard navy day’ - and has a defined growth path to 40 MW and later to 44MW. The engine is compact and its specific fuel efficiency at high power is better than many naval high-speed diesels.

### 5. CRUISE ENGINE

Fast Ferries adopt power dense high-speed diesels for installed power up to about 32MW, beyond that high-speed diesels are coupled with gas turbines to deliver high maximum powers. Fast Ferry propulsion configurations are designed to operate with maximum efficiency at high engine rpm where the craft will mostly operate.

**Figure 5** Pielstick PA6B STC Propulsion Diesel
Figure 5 shows the Pielstick PA6B STC propulsion diesel selected for Lockheed Martin Littoral Combat Ship (Picture - Fairbanks Morse). This engine not only offers the benefits of the wide torque band available with sequential turbo-charging and the US Navy shock qualification but also offers class leading low fuel consumption; an essential attribute to any ocean going vessel.

Combatants conduct extensive low speed operations where just a few hundred kilowatts from say a pair of 8000kW engines poses a particular demanding operation. Few diesel engines are comfortable operating in this manner; MTU and Pielstick are two examples of engine manufacturers with engines designed to meet this duty cycle.

In Fast Ferries, shaftlines are normally configured with each engine driving its own waterjet but for a fast combatant with its extensive time spent at low speed this would mean considerable time spent with some of the jets trailing leading to reduced propulsive efficiency. Combatants, therefore, will tend to operate all jets at all speeds and for many configurations this will lead to the diesel engine seeing ‘double torque’ demand from the propulsors. In order to avoid multi-speed gearboxes the diesel is likely to be ‘sequentially turbo-charged’ thereby gaining a very wide torque and power curve. The engines capable of delivering these characteristics, illustrated in fig 6, tend to be the same as those mentioned earlier as suitable for extended low speed operation.

For large fast combatants the choice of waterjets will be between the plug-in SII type, from about 40 cm up to about 215 cm diameter and the VLWJ (Very Large Waterjet) from 220 cm diameter onwards. Figure 8 shows the simplified selection range based upon delivered power and ship speed. This should only be used as a guide as the actual ship configuration and operation can influence the selection one size up or down. Action damage, where one or more jets (or shaftlines) are non-operational, can also be an important consideration.

6. WATERJETS

Waterjets display different efficiency characteristics from a screw propeller in particular they have higher efficiency at speeds beyond 30 knots but generally worse below 25 knots [6]. This is illustrated in Figure 7.

The fast combatant certainly demands high-efficiency at high-speeds to contain the total installed power (as well as the very high waterjet power-density) [6]; the lower propulsive efficiency at lower speeds has a lower impact on fuel consumption even though considerably more time is spent at low speeds. What the lower propulsive efficiency at lower speeds does do however is to affect the calculation of ship’s bunkerage which is normally a calculation of fuel burn at a specified transit speed; in the case of a typical littoral fast craft fuel burn will be of the order of two tonnes per hour at 20 knots giving 300t of useable fuel for 3000 nautical miles. At 45 knots however fuel burn is about 15 tonnes/hour; 300t therefore gives a range at high speed of only 900nm.

**Figure 7** Waterjet and Propeller efficiency

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**Figure 8** Waterjet Selection   shaft power vs ship speed

The Rolls-Royce Kamewa SII range of stainless steel waterjets are the most commonly used waterjets in
large fast craft and have recently been selected for the US Navy X-craft as well as Lockheed Martin’s LCS. The waterjet is assembled in the factory and shipped as a complete unit ready to ‘plug into’ the prepared transom seating arrangement. Power is taken directly onto the substantial transom structure leading to lower overall weight arising from the absence of a separate thrust block and supporting structure. This arrangement means that in the event of waterjet damage any jet change can be conducted rapidly and usually without the need to dock the vessel. Seven blades are used to ensure optimum efficiency and reduced noise transmission. The SII is illustrated in Figure 9.

Figure 9 Rolls-Royce SII range of Waterjets showing the plug-in concept

The VLWJ range is too large to ship as a pre-assembled unit. It is designed for assembly at the shipyard with the thrust bearing on the shaft line within the ship although with the VLWJ Rolls-Royce adopts an active thrust bearing to dynamically control impeller tip clearance thereby maintaining a high efficiency throughout the ship operation. The jet has been selected for the large SES Techno Superliner and will feature twin 235 units for ship speeds of around 40 knots. The VLWJ is illustrated in Figure 10.

Figure 10 Rolls-Royce VLWJ

7. PROPULSION SYSTEM CONFIGURATIONS

Propulsion systems for large fast ships, at least up to 130m, have, of course, been delivered and are operating well. These systems are applicable to the largest fast (>35 knots) monohulls and consist of large high-speed diesels and gas turbines configured to drive individual waterjets through independent shaftlines. These ships spend the majority of their time at high speed with lower speeds only being used on entry to or exit from harbour. Figure 11 illustrates a typical propulsion system configuration.

Figure 11 Example Fast Ferry Propulsion Systems

Fast Combatants have a quite different operational profile. Fast transit speed is necessary for early entry into the operational area and for intermittent operational tasking but these warships will also spend large proportions of operational time within the 10-20 knots speed range or lower, [7].

Figure 12 Fast Ferry Operational Profile

Figure 13 Fast Combatant Operational Profile
A propulsion system that is configured on independent shaftlines, which is entirely suitable for fast logistics and commercial fast ferries, will use trailing waterjets at lower speeds and power. This leads to a significant propulsion efficiency drop in what is a high-usage speed range. Whenever possible the propulsion system for fast combatants should be designed to drive all fitted waterjets at all times and should drive the largest number of waterjets possible, [6] see figure 14.

![Figure 14](image) Comparative efficiencies of typical Fast Ferry and Fast Combatant propulsion systems through the ship speed range

An example of a propulsion system configured for a Fast Monohull combatants requiring between 60 and 80MW might be as illustrated in Figure 15

![Figure 15](image) - typical monohull fast combatant propulsion offering 72MW in a CODOG configuration

A similarly powered trimaran presents a greater power density challenge but with careful configuration a twin GT CODOG solution can be installed - Figure 16.

![Figure 16](image) - typical trimaran fast combatant propulsion offering 72MW in a CODOG configuration

Both monohull and trimaran systems shown in figures 15 and 16 operate all waterjets at all times. Both use high-speed diesels for cruise and transit speeds with the MT30 marine gas turbine being used for maximum speeds. The monohull allows the use of the slightly more efficient quad waterjets whilst the trimaran system uses two jets only due to space constraints. The trimaran system can however deliver very efficient single gas turbine operation with either of the two Gas Turbines.

The Surface Effect Ship (SES) represents the most difficult propulsion system configuration. A 2000T vessel will be optimised for on cushion performance at high speed requiring 60-70MW of propulsive power plus an additional 5-10MW of lift fan power. Due to the constrained nature of the hull and the sensitivity to weight it is unlikely that a combined electrical system can be used for lift fan and propulsive power; it is usual to install mechanically separate systems. The hull form of the SES relies on the high on-cushion length to beam ratio of the hulls to reduce resistance. This architecture presents a more extreme physical envelope for the propulsion plant than the catamaran. Typically the hulls will not allow for any horizontal offset in gearing and a vertical configuration must be chosen. Where cruise and transit capability is required the designer is inevitably driven towards CODOG or CODAG plants utilising a mirrored propulsion train in each hull. Due to spatial constraints the gearing poses a major issue in that the gearing inputs should be configured with the highest speed input (GT) at the top, diesel in the middle and output at the bottom. In order to provide adequate
clearance for shafts, diesel sumps and gas turbine combustion air the vertical configuration can lead to machinery plants of 3 or 4 decks in height.

7. PROPULSION SYSTEM PERFORMANCE

Having considered the different characteristics of the competing hull forms this paper will now examine the performance aspects of a twin MT30 CODOG solution (similar to Figure 15) installed in a representative Fast Monohull Littoral Craft of about 4000t displacement.

Figure 17 – Operation of a 72MW quad waterjet propulsion system in a CODOG configuration

Figure 17 shows the speed range and rpm for the prime movers as well as the waterjet rpm for a typical 70MW fast littoral combatant running four size-160 seven bladed Rolls-Royce waterjets.

A pair of High-Speed diesels will provide economic low speed operation up to 22 knots after which the gas turbines operate and take the craft to full speed of almost 50 knots.

Figure 18 – Fuel Burn and Operational Profile

Inevitably when operating at high speed the ship will burn considerable quantities of fuel: this would be so whether driven by high-speed diesels or by marine gas turbines. Fuel consumption of about 210 grams per kW hour at 72 MW leads to approximately 15 tonnes of fuel per hour. Fuel consumption per hour for the CODOG system is shown in figure 18 and also plotted on the graph is a typical operational profile for a craft of this type.

Fuel burn is very much the product of the sheer amount of power required for such a large fast craft rather than the technology delivering power. With a specific fuel consumption of about 210g/kWhr, MT30 betters many large high-speed diesels at full power and part power is delivered through high-speed diesels matched to a lower cruise or transit speed. Range can demonstrated as in the following figure 19.

Figure 19 – Nautical Miles per tonne of fuel

Fuel consumption and bunkerage represents the Gordian knot of fast combatant design. Naval commanders expect vessels of 80-100metres to be able to operate independently, worldwide and this leads to very high transit endurances at modest speeds. Fuel consumption at very high speeds is inevitably high though there will be a balance between transit and full speed endurance. Dependant upon the operating profile chosen for the vessel, one of these endurance cases will prevail as the driver for sizing fuel tanks. This can lead to a vicious design spiral of increasing fuel load, increasing displacement, increasing full speed power, increasing fuel load where the lower speed case sizes the tanks.

Correct management of the balance of propulsive power between cruise and boost engines as well as efficient gearing solutions with maximum use of waterjets will improve cruise performance whilst maintaining boost efficiency. With fuel burn volumes at these magnitudes (similar to a large conventional destroyers) in such a small vessel which is likely to be sensitive to trim or in the case of a stabilised monohull, also likely to be sensitive to draft, the management of fuel quality, the movement of fuel around the ship whilst underway, and the replacement of fuel by ballast water are areas of design which will require considerable attention.
9. SUMMARY

Large fast Littoral Combat Ships operate beyond the main hump and demand a high level of installed power in a ship of relatively compact dimensions. Combat ships operate for long periods at loiter and transit speeds and only briefly at maximum speed which demands a propulsion system configured for at least two operational ranges imposing specific and demanding requirements on each propulsion equipment. Weight and space are critical and the power density demands are extreme. Fuel management, both its supply and its use in optimising on route trim and draft, will be an important design consideration.

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