TECHNOLOGY ENABLERS FOR A FAST MILITARY SHIP

BY

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ABSTRACT

There has been an increase in interest in 'Fast Ship' concepts over the last year. Several concepts have been widely presented and the requirement for higher top speeds has been debated. However little detailed consideration has been given to the availability of the required enabling technologies. The UK MoD has now identified 'Fast Ship' as a priority area for investment recognizing that the Future Surface Combatant and the 'Maritime Afloat Reach and Sustainability' vessel are potential high-speed platforms. The power requirements of a ship capable of sustained speeds in excess of 35 kts are established and the consequent marine system challenges are discussed. It is concluded that in the short to medium term there is no alternative to gas turbine prime movers and waterjet propulsors. It is further identified that although direct drive mechanical is the self evident choice through considerations of power density and full power efficiency, there may be a case for a hybrid system to provide a loiter drive for a Fast Combatant, although such a system is unnecessary for a Fast Transport ship.

Introduction

The first part of the twentieth century saw a step change in warship capability when the DREADNOUGHT class adopted the then new technology of marine steam turbines to provide greater power density than ever before. Since those revolutionary days speed has remained important but now, with the concept of rapid reaction forces and littoral warfare, there has been a resurgence of interest in high speed. As a result the naval market has recently shown significant interest in adopting larger fast ship types and this has generated a requirement for much increased power and torque density for propulsion equipment and systems. This article looks at the implication of these Fast Ship concepts on marine power systems for naval vessels.

It is of note that it is not just in the military arena that speed is becoming increasingly important, the adoption of lightweight structure; better, more power-dense engines and waterjets has changed the design and operation of passenger ferries over a large number of routes. Instead of travelling at around 20 knots, many ferries now regularly exceed 35 knots. On smaller high-speed ferries the propulsion system designs are dominated by high-speed diesels and catamarans are common as the hull form. Nevertheless larger ships operating on longer routes are predominantly mono-hull vessels and are mostly gas turbine or combined gas turbine and diesel powered. Both these types of vessels have synergy with the ambitions of naval designers considering military fast ships. It may well be that these commercial developments have given naval designers confidence that large fast warships are becoming feasible.

Fast Ship definition

Due to rapidly reducing propeller efficiency, the speed limit for conventional propellers is around 35 kts. Thus vessels requiring high endurance, good payload and operational speeds above 35 kts require novel propulsors and these vessels can all be considered generically as Fast Ships.

Operational Profile

Many of the marine systems issues associated with Fast Ship relate to the envisaged use of the vessel. For this article two broad operating profiles are considered, which are shown pictorially at (FIG.1).

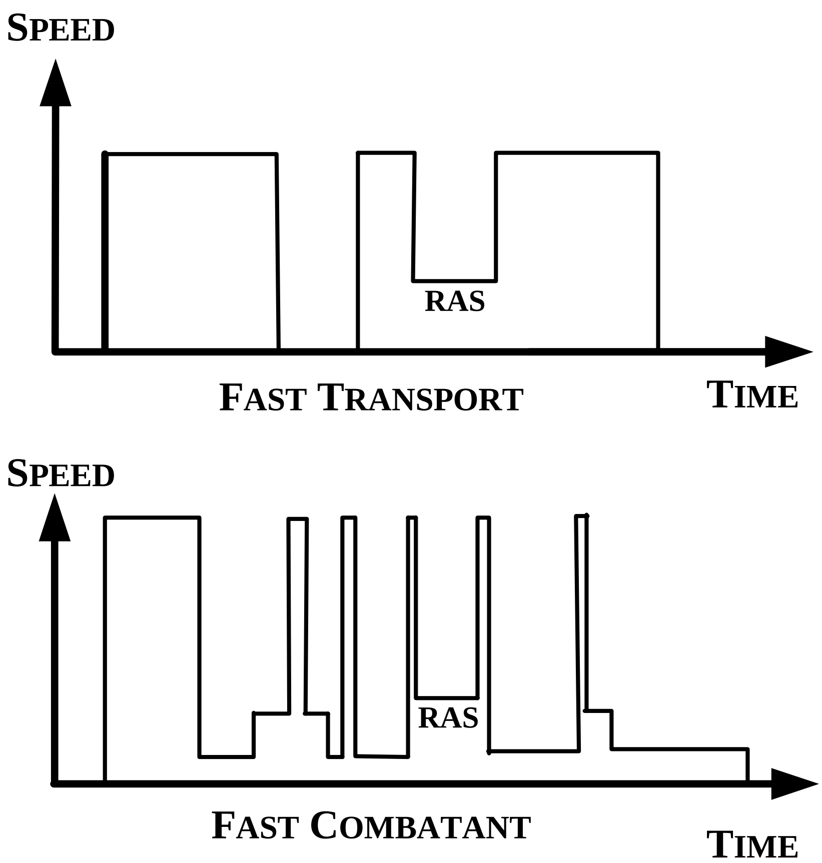

FIG.1 – TYPICAL GENERIC MISSION PROFILES

Fast Transport.

Sailing from a port, transit at high speed, dock, unload, RAS and return at high speed. This profile is that of a fast heavy lift vessel. The top speed of the vessel is dependent on achieving a balance between fuel load and cargo load as well as the relative benefits of investing in fast load/unload times and high transit speed. Speeds of up to 80kts have been postulated for vessels of this type.

Fast Combatant

Fast transit speed 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 kts speed range or lower. Speeds of up to 65 kts have been suggested in concept assessments for vessels of this type.

This article does not consider small vessels (less than 1,500 tonnes) with low endurance such as fast attack/patrol vessels suited for coastal operation.

Recent Fast Naval Vessels

Both Norway and Sweden have developed lightweight, composite structure, gas turbine and waterjet powered fast naval craft. The US has acquired a number of fast logistics vessels and has recently ordered the catamaran based X-craft (known earlier as the LCS) both of these current USA types of Fast Ship are of lightweight aluminium construction and are propelled by waterjets.

During the 1990s, Rolls-Royce was contracted to design a Fast Ro-Pax by a commercial customer. The hull form was developed to carry a very high deadweight whilst being economically constructed largely of steel. To further improve the economics a very low resistance hull-form was developed incorporating a number of innovative design features including gas turbine propulsion. The Rolls-Royce Fast Naval Sea-Lift Vessel was an obvious progression from this commercial design because of the developing fast naval logistics market and its need for high dead-weight. The Rolls-Royce Fast Naval Sea-Lift Vessel realises high payload with good endurance, and is of robust steel construction with good damage stability and an artist's impression is at (FIG.2).

FIG.2 – THE ROLLS-ROYSE FAST NAVAL SEA-LIFT VESSEL

Future Naval Vessels

With regard to fast ships in general the UK MoD has identified Fast Ship as a priority area for investment and recognizes two potential Fast Ship Platforms: Future Surface Combatant (FSC) and Maritime Afloat Reach and Sustainability (MARS). The USA also has an interest in Fast Ships, notably the Littoral Combat Ship (LCS) and the Theatre Support Vessel (TSV).

Marine System Challenges

Fast Transport

Commercial vessels of this nature are available today. Catamaran hulls are in use as fast ferries in many areas of the world and the USN has chartered such a vessel for assessment. Other hull forms that should enable greater payloads are under development along with their enabling technologies, the European IZAR vessel and the commercial Fast Ship Concept being examples. The operating profile of these vessels makes efficiency at high speed and payload the dominant considerations, efficiency at low speed is not of particular importance. In the military application the need for enhanced survivability and flexibility of operation over that of commercial vessels must be considered. The size, performance and payload of these vessels is constrained by the availability of high power gas turbines and waterjets, their efficiency and the limited options for machinery configuration within the required novel hullforms. Vessels of this nature are sensitive to trim and require positive management of loads and fuel to ensure optimum performance. The benefits of such vessels are undermined if fast turn round in port cannot be achieved.

Fast Combatant

The fast combatant is a far more complex vessel than the Fast Transport being of a full military specification with resilient services provided to combat systems along with the ability to withstand battle damage. This vessel needs not only to have the required level of endurance at high speed but must also meet efficiency and signature requirements in the 10-20 kts operating band. These requirements are likely to result in the need for boost and cruise configurations in the propulsion system, increasing complexity and system weight and volume. Heat management in conventional combatants is an issue of increasing importance and this is exacerbated by the high power levels required for a fast ship and the limited hull area for cooling water intakes and exhausts. Advanced hull forms present new problems for the retention of stability in the damaged state requiring more sophisticated control mechanisms than those currently employed.

Flexibility

Some concepts for fast vessels include re-role capability and reconfigurabilty. These concepts enable the carried payload to be optimized for the operation being undertaken, in doing so the cost and size of the platform is reduced. The options include the ability to embark additiona1 fuel tanks to increase endurance during fast passages. All such capabilities require the ability to embark and disembark alternative loads rapidly, either while deployed on operations or in port. This requires mechanical handling, locating and securing devices, rapid connections and reconfigurable ship's systems. Although none of these represent a daunting challenge in their own right there are few existing systems that could be developed to meet this new requirement and so the risk is difficult to quantify.

Hullform Constraints

A slender hullform at the waterplane constrains design flexibility and may limit useable volume, a balance between high-speed sprint, endurance, size, displacement and sea-keeping results. Likely contenders in addition to a monohull (which may be preferred because of the space it allows for high power equipment) are:

> Catamaran, Trimaran, 'Slice', SWATH, Surface Effect Ship (SES) or perhaps even hybrids of these already novel hullforms themselves.

In addition to the obvious constraints on design flexibility with respect to marine engineering systems there is also likely to be a serious constraint on crew size, to minimize hotel services and provisions although additional personnel could perhaps be transported as part of the flexible payload concept.

The need to reduce weight may result in the requirement for advanced materials in marine and structural systems with consideration given to the wider application of titanium, magnesium alloys, 'metal sandwich' and composites. Options will need to be analysed in terms of their battle damage performance and through life cost as well as structural strength.

Power Requirements

The most recent vessels in the Royal Navy have specific power levels (relating total shaft power to ship displacement) of:

5.4 kW/tonne for the T45 Destroyer and 0.45 kW/tonne for the AOR.

A simple comparison of military to commercial propulsion power density therefore indicates a 10 fold difference. Table 1, illustrates the propulsion and installed power necessary for various types of hullform.

TABLE 1 – *Comparison of High Speed Hullform Technologies*

Hullform	Displacement (tonne)	Speed (kts)	Range (nm)	Payload (tonne)	Installed Power (MW)	Power to Displacement Ratio (kW/tonne)
Catamaran	3,900	45	1,250	1,500	115	29.5
Monohull	6,200	50	1,500	1,500	145	23.4
SES	12,300	70	5,000	4,500	685	55.7
Trimaran	10,300	55	8,700	4,500	360	35

High power and high density propulsion probably demands gas turbines, compact reduction gears and waterjets. SES demand lift fan and seal system development. Lift fan designs require a combination of pressure and flow, which represent the top end of the state-of-the-art in centrifugal compressor design. Seal technology for high speed, high cushion-pressure, ocean-going ships would need investigation for military application.

Gas Turbines

Gas turbines are the most power dense prime movers currently available and are the power source of choice for large high-speed vessels. This is not predicted to change in the medium term. At present the largest marine gas turbine that could be available over the next 10 years, given the required market conditions, is the Rolls Royce Marine Trent, available now as the MT30 (FIG.3) and currently providing up to 36 MW (but with a defined upgrade path to 40MW and with the potential for 45MW), and this is to be followed by the MT50 rated at 50MW. Higher power developments, up to 90 MW, have been proposed by manufacturers and are considered feasible given appropriate investment.

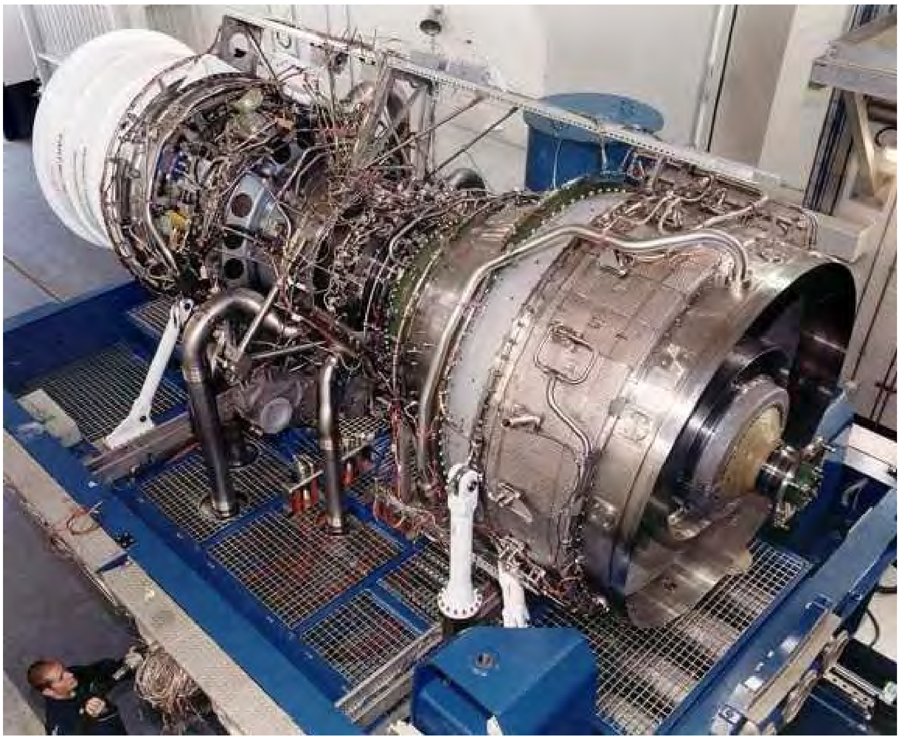

FIG.3 – THE ROLLS-ROYCE MT30 MARINE GAS TURBINE

All these engines are simple cycle and as a result do not have the efficiency levels of advanced cycle engines at part load. However the increased size and weight of advanced cycle engines make them unattractive for fast ships. Smaller cruise engines will therefore be required for the combatant during low speed operation, unless an electrical Hybrid system is adopted and the propulsive electrical power provided from integrated ships service and propulsive prime movers. Research into more efficient gas turbines will improve the performance of simple cycle engines though a proportion of this improvement will be counteracted by increasingly challenging environmental legislation.

The machinery configuration of fast transit vessels will probably be able to use a combination of identical high power engines, the operating profile not making low speed efficiency a driver. Unless using a Hybrid system for fast combatants the total number of prime movers is likely to be increased by the need to meet low speed requirements.

Transmission

Propulsion machinery must be compact, lightweight and fuel efficient, yet produce and transmit very high levels of power. The three options available to transmit the power between the prime mover and the propulsor are discussed below.

Mechanical

Where reduction gearing is required, epicyclical gears, offer very high power density, and have a significant heritage. As a consequence a programme aimed at navalising an epicyclical gearbox at the torque and speed requirements for a Fast

Ship should not be prohibited by risk or timescale. Epicyclical gearboxes are not, however, suited for use as a combining gearbox (as required for a cruise-boost arrangement for a combatant). Parallel shaft gearboxes are dominant in Naval use and there is no doubt that gearboxes of the required capability are available now although the ship volume constraints may increase risk and cost and perhaps make an epicyclical gear box preferable for the Fast Transport.

Electrical (IFEP)

With current technology Integrated Full Electrical Propulsion (IFEP), as shown at (FIG.4), is bigger and heavier than its mechanical equivalent. Without significant and uncertain development of electrical equipment – both motors and converters – mechanical drive systems offer improved power densities and better full load efficiencies over equivalent integrated electric drive. Although some reduction in motor size can be achieved by using a gearbox some of this advantage is lost in the additional equipment volume of the gearbox itself and the size of the converter is not altered at all. As a consequence, for Fast Combatants IFEP solutions are certainly not feasible. In addition the operating profile of the Fast Transport does not allow IFEP to generate its part load efficiency savings – the full speed operating point dominates and here direct drive geared mechanical is always more efficient. In summary the volumetric and weight constraints, or the operating profile, of the Fast Ship concept, together with the very much higher power levels required, drives machinery selection to direct mechanical drive. This hard fact remains even when taking account of the increased rotational speed associated with a waterjet when compared to a propeller. If further evidence were needed that IFEP systems are not suitable for fast ships; heat management and rejection is also likely to pose problems and these will be exacerbated in the case of IFEP systems with their higher full load losses.

In parallel with the increasing interest in fast ship there is also an increasing interest in the deployment of pulsed energy devices. These devices include electromagnetic (EM) Guns, high power radars and sonars and EM launchers. The arrival of IFEP Systems is considered to be an enabler for high energy weapons as it results in electric distribution systems with sufficient capacity to power these devices in a resilient manner. However many of these pulsed power weapons have a power level (and rise transient) way beyond the capability of a marine electrical propulsion system – the necessary very low system impedance for an electromagnetic weapon cannot be provided from a propulsion system rated for several orders of magnitude lower power transmission. That is not to say that the IFEP power system does not bring some benefits for EM weapons, but simply that they are not as large as may be imagined because some form of energy storage and power conditioning will be required.

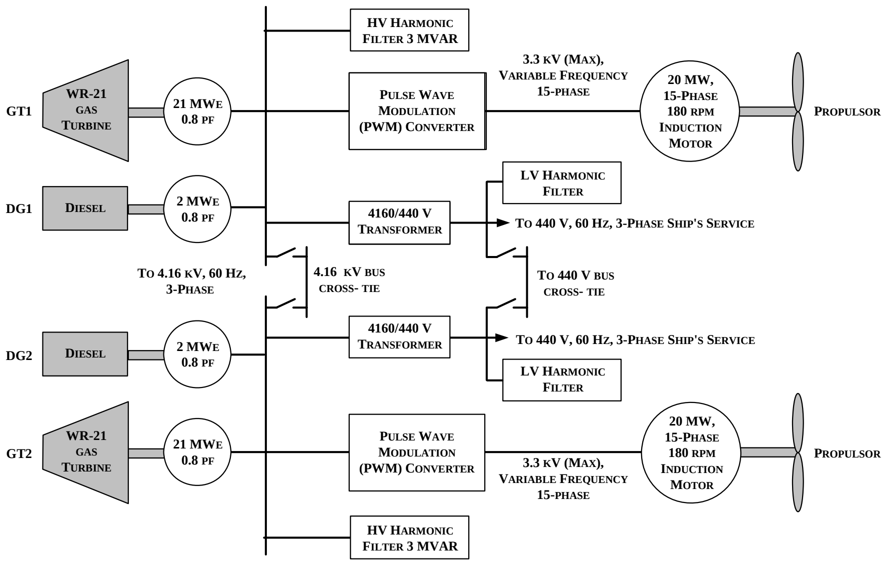

FIG.4 – AN ARTIST'S IMPRESSION OF THE TYPE 45 DESTROYER AND A SIMPLIFIED SCHEMATIC OF ITS PROPULSION SYSTEM

Hybrid Transmission Systems

In the specific case of Fast Ship hybrid propulsion systems could be taken to encompass more than just the electro-mechanical transmission hybrid of the T23 frigate, although a variant of this is undoubtedly an option. Another propulsion configuration that might deserve the term Hybrid is one with a mix of waterjets and propellers as propulsors – propellers for cruise and waterjets for boost. However these will be dealt with later on in this paper as this section is focussing on power transmission between the prime movers and propulsors.

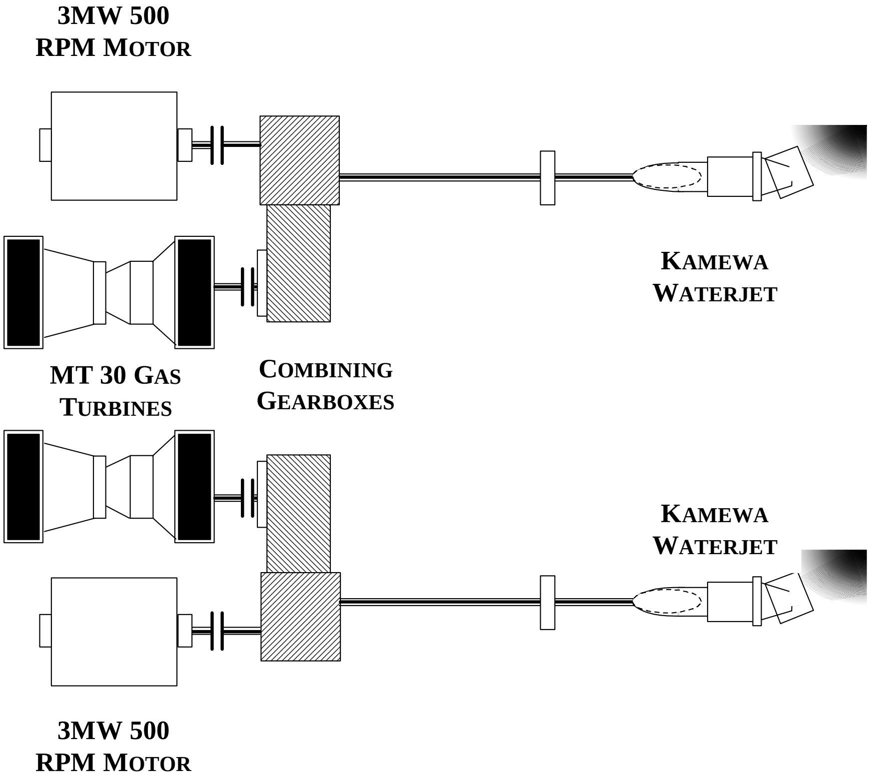

FIG.5 – A GENERIC FAST LITTORAL SHIP HYBRID PROPULSION SYSTEM SCHEMATIC

Efficiency at slow or perhaps transit speeds may suggest a hybrid transmission system. An electrical hybrid arrangement, as shown at (FIG.5), may be possible depending on:

- The available space.
- The speed of the motor (dependant on where it connects into the drive chain).
- The required power.

In addition, the motor could either drive a larger rated waterjet at part load or provide a dedicated drive to a matched water jet. In either case the advantage in this arrangement would be increased part load efficiency and potential reduction in the total numbers of prime movers fitted and this will need to be balanced against increased complexity and the additional ship design challenges.

Transmission - Conclusion

The most power dense means of powering a waterjet is by direct coupling with a gas turbine. In addition motors with the power rating and power density required for an IFEP Fast Ship application are not currently available. Nor are navalised distribution system elements capable of working at the voltages required to manage fault levels available without development. The conclusion therefore is that a Fast Ship will use a direct drive geared mechanical transmission system to connect a gas turbine to a waterjet. However in the particular case of a Fast Combatant a loiter drive system provided by an auxiliary electrical drive in a Hybrid arrangement may prove advantageous.

Propulsors

Propellers

The propeller is not suitable for a Fast Ship. Although high speed propellers are feasible they operate with very low propulsive efficiencies and this is not acceptable because of the overriding need for full power fuel efficiency.

Waterjets

In the near to mid term, the waterjet is the only likely technology capable of generating sufficient thrust for high speed. High power units are required to minimize the number fitted, hence waterjets rated at 40 MW and higher are under development but not currently available (Rolls-Royce has a design for a 49 MW waterjet which has not yet been built and the current portfolio includes a 36MW waterjet). In slender hulls the waterjet has little impact on the hull design, however, the hull influences the waterjet design, where flow irregularities in the inlet are major factors in the design of ducts, stators and rotors. Resistance, sinkage, trim and the draw-down of the water surface in the vicinity of the waterjet need to be considered. Consequences of a lack of integration are reduced efficiency, higher fuel consumption and operational limitations in waves. Waterjet technologies, of which an example is at (FIG.6), include Mixed Flow, Single Stage Axial and Two Stage Axial and can be steerable or non-steerable. Assessment and understanding are required as the Royal Navy has no experience with these devices. Waterjets are not efficient across the operating profile, which either demands a hybrid system or development of adaptable solutions (which are feasible but would significantly increase complexity).

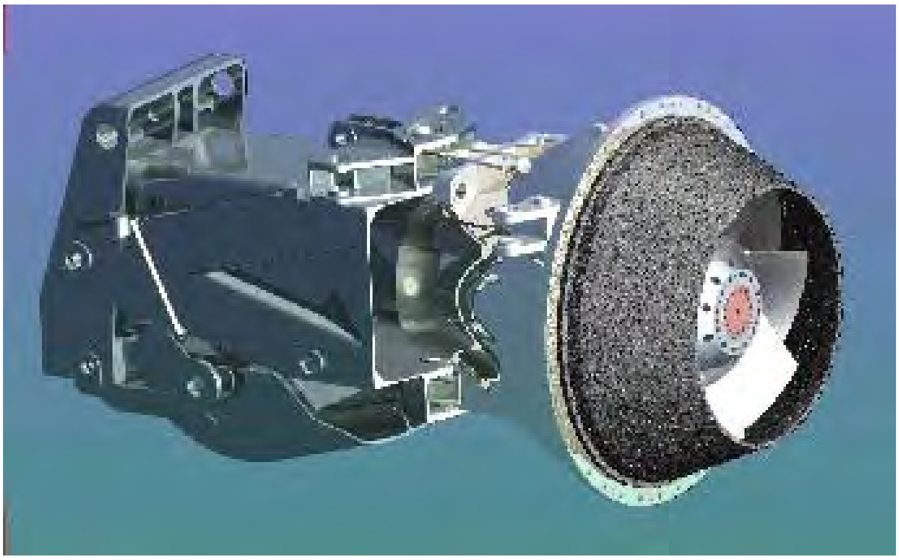

FIG.6 – THE ROLLS-ROYCE S2-11 WATERJET

The choice of waterjets, numbers and sizes is one of the key aspects of the overall system design. Clearly for a Fast Transport Ship several waterjets of the same size would be appropriate. However in the case of the Fast Combatant some form of father-son arrangement will probably be best suited to the operating profile. Some typical mechanically driven waterjet configurations are as follows:

- Two individual water jets.

  Each driven by a small and a large prime mover either in 'AND' or 'OR' arrangement through a combining gearbox.

- Four individual waterjets.

  Each separately driven by a dedicated prime mover, which may be identically sized, or in a large and small arrangement depending on the operating profile.

- Four water jets in two pairs.

  Each pair driven by two prime movers through a 2 input 2 output combining gearbox in either 'AND' or 'OR' arrangement.

It should be noted that trailing waterjets leads to a significant efficiency drop therefore the system should be designed to drive all fitted waterjets wherever possible. In addition and as shown in the graph in (Fig.8), a system with four waterjets has better efficiency than one with two.

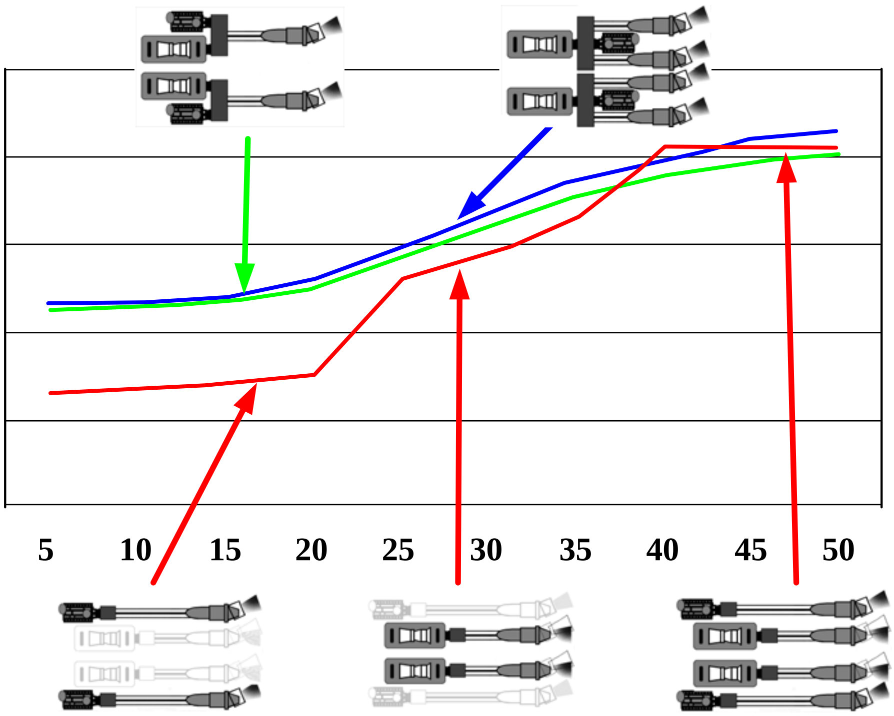

FIG.8 – THE IMPACT OF THE NUMBER OF WATER JETS ON OVERALL EFFICIENCY

The gear box requirements for the above configurations are all available now. At most the reduction ratio would be 13:1 and probably lower, depending on the optimum prime mover speed for the required power. It is of course practical to provide a Diesel Engine as the smaller prime mover although the reduced power density must be included within the overall ship design. As previously mentioned an electrical hybrid arrangement may be possible to provide efficient part load drive to the waterjets, in place of the 'father-son' arrangement.

A lack of experience with military waterjets needs to be overcome. Shock performance is not well understood, although manufacturers do not consider this to be a difficulty. LIPS are supplying waterjets for the South African MEKO A200 Frigate, which have been adapted for shock withstand. Whilst high speed noise signature is not of great concern the Fast Combatants signature at low speed may be important. Large waterjets are not currently available that meet current signature requirements and no large waterjets have undergone shock testing. Additional work will be required to provide a naval waterjet of sufficient power for Fast Ships. However the 8 MW Rolls-Royce SII-LM waterjet, as fitted in the Swedish VISBY Class, has considerable naval features including:

- Low noise.
- Low magnetic signature.
- High shock capability.
- Low weight.
- Control system with good EMP resistance.

Therefore the overall risk to producing a large navalised waterjet should be acceptable.

Pods

Pods use propellers and are therefore inherently unsuitable for military Fast Ship designs. The European Union is funding a FASTPOD project for fast commercial ships but this has a target speed of only 35 kts and is therefore not applicable.

Hybrid Propulsor Systems

The difficulty with waterjets is with providing adequate slow speed (less than 20 kts) efficiency, one solution is to use propellers for the lower speed range and waterjets for the boost higher speed range. The problem with this approach is that the propellers (and their associated shafting and A brackets) impose very large losses when propelling at high speed. So much so that the advantages are more than cancelled out, particularly when the high speed operation is the principal feature (that is not an occasional sprint as with most current day warships). This new operating profile for the Fast Ship mitigates against the use of hybrid propulsor systems. However there is one example in existence, albeit not a Fast Ship since its top speed is less than 35 kts, the Amatola WARP (Waterjet and Refined Propeller) drive for the South African Navy MEKO A200 consists of 2 diesel driven controllable pitch propellers and 1 gas turbine driven waterjet.

Fuel

The issue of fuel should not be understated. The concept of rapid reaction and fast transit is at the very heart of the Fast Ship concept for both varieties. Transport and Combatant operations start with an extended passage at very high speed. It is to be presumed that there will be little notice of operations and thus no time to pre-load the transit route with auxiliary replenishment ships. Therefore a Fast Ship must sail with enough fuel to complete its mission, no easy task. For the Fast Transport Auxiliary fuel tanks as part of the payload during ocean transits may be feasible, hence an open system architecture is required but nevertheless this issue reinforces the overriding need for fuel efficiency at full power. It may be possible, in a configurable vessel, for a Fast Combatant to be fitted with auxiliary fuel tanks for the transit phase, which might be removed or replaced in theatre.

Maintenance of Stability and Trim/List

Novel high-speed hullforms will present unique hydrodynamic behaviour and the requirement for a stable platform for weapon systems and the operation of helicopters may require analysis and development.

Fluid management is required to provide adequate static and dynamic stability to ensure safe and efficient ship operation in damaged and intact states. Optimal manning will demand intelligent, integrated LAN based systems and reconfigurable spaces will provide built-in flexibility. Automated damage control and firefighting systems are required to support optimal manning, to include detection, classification, and management of fire, heat, toxic gases, flooding and structural damage.

Mechanical Handling

Design constraints will not allow multi-role hull design hence mission reconfigurability is essential. Fast turn around for mission reconfiguration demands flexible, open architectures and fully interchangeable mission modules. Automated replenishment at sea and alongside should be considered for all logistic products. The US Littoral Combat Ship (LCS) is proposing common controls and common deck handling equipment with extensive use of robotics.

The size/weight of cargo handling systems will impact upon ship speed and/or payload, however, the turn around and re-role efficiency of the platform will impact upon mission cycle. Assuming the vessel will be required to RAS, it must be compatible with replenishing units at a given RAS speed (nominally 12-14 kts).

Thermal Management

Fast ship presents challenges for thermal management, which is already an unresolved issue for conventional vessels. The interface with the sea water heat sink at high speed needs consideration and with novel hullform there may be limited space for fan intakes and outlets. This must also be considered in the context of providing a low RCS signature. In doubling the propulsive power the rejected heat is also doubled. In an IFEP solution, novel technologies such as superconducting machines or high temperature power electronic devices might be the only solution.

Conclusion

The military Fast Ship deserves its high profile; the operational advantages that such vessels would bring are unarguable. However as has been demonstrated in this article there are significant marine systems challenges that need to be overcome if they are to be realized in full. The following is a list of these challenges:

Naval Architecture

- The hullform must be designed to square the circle of high deadweight capacity to low hydrodynamic resistance.
- Stability of novel hullforms, if adopted, must be ensured, at all stages of a transit as fuel load lightens. This may require active control of on board loads.

Prime Movers

- The prime movers in a Fast Ship must be powerful, power dense and fuel efficient at full load. Large gas turbines are available now and further units of even higher powers are being developed. However there may be a need for a fuel efficient gas turbine rated somewhere between 5 and 10 MW to provide the cruise drive at acceptable efficiency, it is possible that this engine could benefit from recuperation if the weight and volume penalty can be kept low.

Transmissions

- The transmissions arrangement must be power dense and allow efficient part load performance in the case of the Fast Combatant. The Fast Combatant will require a combining gear box of some form if the transmission is fully mechanical and even for a hybrid driver there will be advantage to be gained through gearing the electric motor drive. Full electric drive is not feasible for the Fast Ship without further revolutionary equipment development. As a consequence epicyclical gearboxes will only be suited to Fast Transports while parallel shaft combining gearboxes will need to be used in Fast Combatants.

Propulsors

- The propulsors must have high power density and be efficient at full load. Further work is required to produce a large naval waterjet though this will not entail unacceptable risk.

It is concluded that in the short to medium term there is no alternative to gas turbine prime movers and waterjet propulsors. It is further concluded that although direct drive mechanical is the self evident choice through considerations of power density and full power efficiency, there may be a case for a hybrid transmission system to provide a loiter or cruise drive for a Fast Combatant, although such a system is unnecessary for a Fast Transport. Without IFEP as a viable option for Fast Ships, the challenge of integrating high energy weapons is significant; indeed they may be mutually exclusive options.