Hybrid propulsion in Feadship's X-Stream and F-Stream concept designs

Hybrid propulsion sounds complicated and expensive and often is… So why have we chosen for this solution?

Generally, hybrid propulsion is deployed when a single propulsion system cannot offer an optimal performance in various operational conditions. For example, while a hybrid car might run perfectly on an electric motor in the city at low speeds and short range, it requires a combustion engine for higher speeds and longer distances on motorways. This engine is less efficient in the city, however, as it consumes fuel even when standing still, cannot recover brake energy and produces exhaust gases.

The same situation applies for ships. A conventional propulsion set-up with diesel engines and screw propellers performs best between normal cruising speeds of 12 knots and a maximum speed of 20. It is much less suitable at lower or higher speeds.

Let us look first at the low speeds. Normally a yacht will sail a minimum of seven knots when the main engines are running on minimum revolutions. A lower speed can only be achieved by controllable pitch propellers or a trolling gearbox. Although modern engines can sail for longer periods of time at low loads, this is certainly not recommended and will produce smoke and soot.

At high speeds, the load on the propellers becomes unacceptably high or a larger draught needs to be chosen to accommodate a larger propeller. An alternative frequently used for high-speed yachts is the water jet. Although this is a good solution, the efficiency of a water jet decreases to below 40 percent at normal cruising speeds. This means large amounts of fuel are required if a transatlantic range is desired, making it an unattractive solution for fast and lightweight yachts. This is why Feadship has built several yachts with a hybrid combination of propellers for the long range and a booster water jet combined with a gas turbine for high speeds.

Figure 1 Hybrid propulsion with controllable pitch propellers and water jet on Ecstasea

Diesel electric propulsion

Diesel electric propulsion is seen as a solution when different operating speeds are required and the power demands are widely divergent. The concept is often applied on cruise ships with high hotel loads and offshore support vessels with major dynamic positioning requirements. Several yachts have been built with diesel electric propulsion, including *Air*, *Ambrosia* and *Kogo*.

Diesel electric propulsion does offer clear benefits such as a flexible arrangement, optimal generator loads and subsequent reductions in emissions and fuel consumption. However, there are also disadvantages on yachts that require high speed, notably the enormous discrepancy between the high power demands needed for maximum speed and the low power demands of a yacht in port with only the crew onboard.

A second problem encountered with diesel electric propulsion is the speed-power relationship of a normal displacement yacht: Propulsion power increases exponentially with speed. Small generators are required to have a flexible power supply at low speeds while large generators are needed for maximum power at high speeds. This means making a choice between large generators, a large number of smaller generators or different sizes of generators. All these options have a downside. Large generators will have a low load when the yacht is in port. A large number of generators demands higher investment and maintenance costs. And differing sizes of generators makes the installation less flexible.

In practice, a combination of all three options is needed. For example, a 80m yacht with a speed of 20 knots could require a maximum power of 8MW for top speed but would only use 300kW in port. At a cruising speed of 12 knots, approximately 1.0 MW would be required. The same megawatt will only add an additional knot at the top speed.

To assure an optimum load in port and have some redundancy, this yacht would require two generators with a maximum power of 400 to 500kW. The remaining power of 7MW should be divided over several generators, and a choice made between the maximum flexibility of a large number of small generators and the simplified system of fewer large generators. Although a logical solution would be to install four to six generators with power ranging between 1 and 2 MW, this basically ends up in a normal installation with three to four small generators and four main engines.

Other disadvantages are the additional weight and space requirements and costs. An 85m diesel electric yacht concept designed by De Voogt, for example, had a speed of over 17 knots requiring a power of 4.5 MW. The generator room with six generators was 11m long, equivalent in size to a normal engine room. However, an additional switchboard room with a length of 8m was required for the converters, switchboards and drives needed for the diesel electric propulsion installation. The weight of the equipment in the switchboard room added around 60 tons to the lightship. The additional costs were in the range of three million euros, although that is still a relatively small percentage of the overall building costs.

Another design which required a higher speed of 25 knots - and consequently a higher power of 16 MW - resulted in an even larger system. In this case, the length of the engine room increased to 15m and the additional weight of the installation to 300 tons.

Pods

It is not only the power plant that needs to be flexible enough to cover all operating conditions; the propulsion system also needs to be efficient, quiet and accurately controllable in all operating conditions. One solution that can meet these demands are podded propulsors, which also offer optimal manoeuvrability.

There are disadvantages to pods, including the required weight (far aft) and draught (restricts sailing areas and harbours). Another is the steering in stern quartering seas where strong steering forces are required to keep the yacht on course. Normally this will be done by the rudders, which provide a sideward lift while the propellers provide full thrust forward. As the pods steer by changing the thrust direction, this can reduce the forward thrust and make for lower efficiency in moderate to high sea states.

One of the latest and largest diesel electric yachts is the 90m Lürssen *Air*, launched in 2005 and renamed *Ice*. This yacht has a propulsion power of 5MW and a maximum speed of 18 knots. Although the speed is not spectacular for a yacht of this size, it still requires a draught of 5m to accommodate the Azipods.

These examples show why a diesel electric propulsion installation is not ideal for yachts requiring higher speeds. At De Voogt we consider diesel electric propulsion a good solution so long as normal speeds are required. For higher speeds we prefer a hybrid system with an optimised installation for low and high speeds.

Concept designs

Feadship has used a hybrid solution on our X-stream and F-stream concept designs: A diesel electric system for low speeds and manoeuvring. For cruising and higher speeds an additional diesel-direct propulsion system is added. The benefits are clear: A clean, quiet and efficient system for low speeds with excellent manoeuvring characteristics, and a light and efficient system for high speeds.

X-Stream

X-Stream is our first concept design and was presented at the Monaco and Fort Lauderdale boatshows in 2006. Some 72m in length, it features lots of glass, an X-bow and a new propulsion system. The idea was to design a concept that included new innovations and ideas while remaining realistic. Feadship expects to be able to deliver such a yacht in 2015. As there was such widespread interest in the design, our research is continuing into both the propulsion system as well as the construction.

The propulsion concept suggested for X-stream is known as a CRP-pod - a contra-rotating propeller combined with a pod. It comprises a diesel electric system driving a pod which is used at low speeds up to 12 knots and manoeuvring. Additional diesel-direct propellers are engaged for higher speeds. Together they form a contra rotating propeller system that improves efficiency by approximately 10 percent (Mämäläinen, 2003, Holtrop, 2006).

For X-Stream we have investigated two pod options; the first with an ABB compact Azipod with the electric motor in the pod, the second with a Rolls Royce Azipull which requires an additional drive inside the yacht. As the maximum torque of the electric motor in the compact Azipod is limited, the maximum efficiency gain could not be reached. A higher torque with lower revolutions is possible with the Rolls Royce Azipull. This leads to a higher efficiency as frictional losses are reduced while rotational losses are recovered with the contra-rotating propeller. In addition, because the body of the Azipull is smaller and more hydrodynamically optimised, it also provides a lifting force when steering.

The CRP-pod solution has already been applied in practice on two ferries built in Japan (Ueda, 2004). These 225m long vessels sail at 30 knots and are powered by a 25MW propeller with an 18MW contra-rotating ABB Azipod. They have been operating since July 2004 and still document a 20 percent saving in fuel consumption (Wheater, 2008). In the above case the CRP-pod system replaces a twin screw installation with one pod and one propeller, therefore offering a even higher efficiency gain.

Figure 2 Hybrid propulsion with controllable pitch propeller and pod on X-stream

F-Stream

Unveiled in 2007, F-Stream is also equipped with a hybrid propulsion system with two new innovations from Voith Turbo. Twin electric Voith Cycloidal Rudders (VCR) are used for manoeuvring, dynamic positioning, zero speed stabilizing and slow speeds up to 10 knots. For speeds of up to 20+ knots, two diesel-driven submerged water jets are engaged and the VCRs (in passive mode) act as rudders.

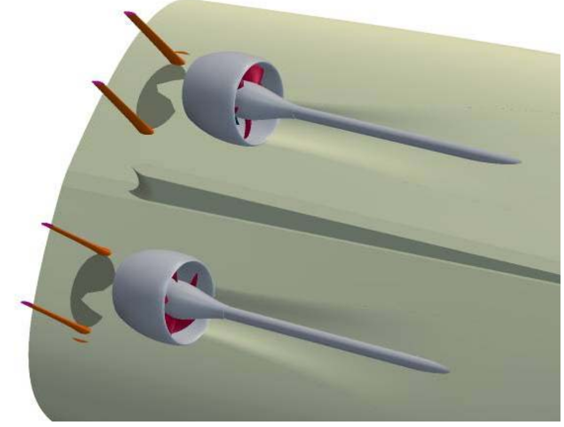

Figure 3 Hybrid propulsion with Voith cycloidal rudder and water jet on F-stream

The new Voith Water Jet (VWJ) has been developed for ships sailing between 20 and 40 knots. The jet consists of a specially shaped nozzle, a rotor and a stator, and can be seen as a combination of a water jet and a ducted propeller.

The jets are submerged and their location under the vessel is comparable to that of conventional propellers. This offers real benefits compared to normal water jets, which are placed at waterline level and make an aft swimming platform impossible. As the jets are placed beneath the hull, no displacement is lost due to the inlet. The diameter of the jet is smaller than a comparable propeller so larger propulsion powers can be accommodated in the limited space available.

Besides the reduced draught, the clearance can also be reduced. While a conventional propeller requires a clearance of between 30 and 35 percent, the nozzle of the VWJ requires no clearance and may even be partly integrated into the hull. The combination of reduced diameter and clearance results in a 20 percent reduction of the required draught, an important consideration for owners looking to sail in shallow waters or smaller harbours.

The jet's cavitation characteristics are better than conventional, highly loaded propellers. The entrance velocity is lower, which increases the pressure and results in a larger cavitation margin. This virtual absence of cavitation creates more favourable conditions in terms of noise and vibration.

The first operational submerged water jet was built by Rolls Royce several years ago. The US Office of Naval Research funded tests on an Advanced Electric Ship Demonstrator, a quarter-size model of a destroyer used for optimising propulsion technologies. Unfortunately the tests were not considered successful enough to warrant continuing the development.

Figure 4 Advanced Electric Ship Demonstrator with submerged water jet from Rolls Royce

In the early 1990s SVA Potsdam and Voith partnered to develop a submerged water jet (Heinke 1994) and in August 2008 the first model tests were carried out in a mutual research project by Voith, SVA Potsdam and Feadship. Approximately 12MW was deployed on each water jet, which with a rotor diameter of 3m resulted in a specific load of around 1700kW/m^2. This is about 40 percent higher than what is considered acceptable on a conventional propeller. For example, on the high speed Feadship *Predator*, launched this year, we used 8.6MW on each propeller resulting in a blade load of 1200 kW/m^2. These first tests have already proven that the efficiencies of the VWJ over the entire speed range are at least comparable to or better than conventional propellers.

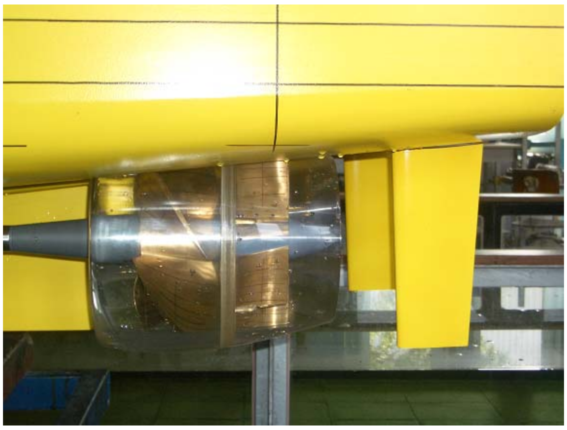

Figure 5 Propulsion configuration with VWJ and rudders during model tests at SVA Potsdam

VCR

The Voith Cycloidal Rudder (VCR), on F-stream fitted behind the VWJ, is similar to a Voith Schneider Propeller, although it has only two blades instead of the usual five to seven. The VCR has two operating modes.

In passive mode the rotor casing only performs partial rotations in both directions. The locked blades act therefore as conventional ship's rudders and can be used between cruising and maximum speed.

In active mode the VCR works as a normal Voith Schneider Propeller. Since thrust and thrust direction can be varied at high rates, the VCR is very suitable for manoeuvring, dynamic positioning and slow speed sailing. The noise levels in active mode are low compared to a sternthruster due to the modest blade loads of approximately 50kW/m². At the same time the VCR can be used efficiently for roll stabilisation. To prove the roll damping capabilities, Feadship and Voith performed model tests for a 60m yacht in 2006. The results showed a large roll reduction comparable to or better than zero speed stabilisers.

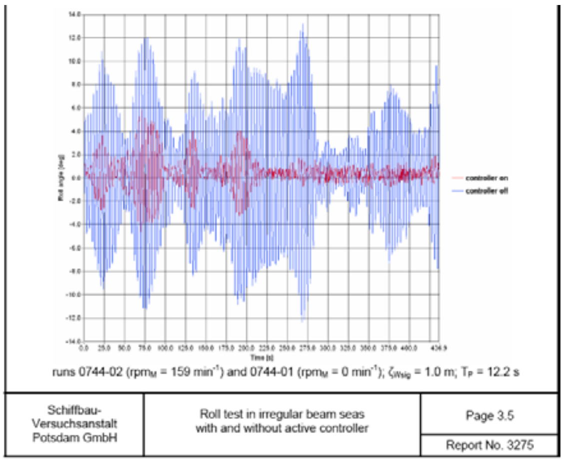

Figure 6 Roll angle with Voith Schneider Propeller on (red line) and off (blue line)

New developments
De Voogt is looking into new developments that might increase the application area of hybrid propulsion and diesel electric propulsion in general. An interesting development is the use of superconductive materials, a presentation on which was given by Rob Rouse from American Superconductor at last year's Global Superyacht Forum. These materials operate at very low temperatures and have near zero resistance, making larger currents possible. As a result, motors and generators can be smaller, lighter and more efficient.

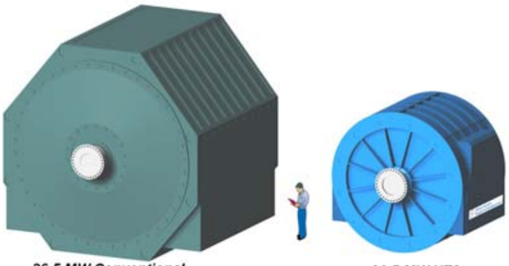

Figure 7 Comparison between conventional and superconducting motor

Conclusion
A hybrid solution offers advantages when optimal performance is required at low as well as high speeds. Although normal screw propellers are an efficient and proven method, manoeuvring and slow speed sailing with the engines working at a minimal load makes for inefficient fuel consumption and increased emissions. Although diesel electric propulsion solves these issues, it requires a heavy, complex and expensive electric system, especially when higher speed (hence propulsion power) is required. While water jets are usually the preferred solution for high speeds, their efficiency decreases at lower speeds. A hybrid installation with different propulsion systems offers the freedom to optimise the system for various operating speeds. It is the best solution when performance at both low and high speeds is required.

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