Wärtsilä waterjets offer powerful and versatile propulsion solutions

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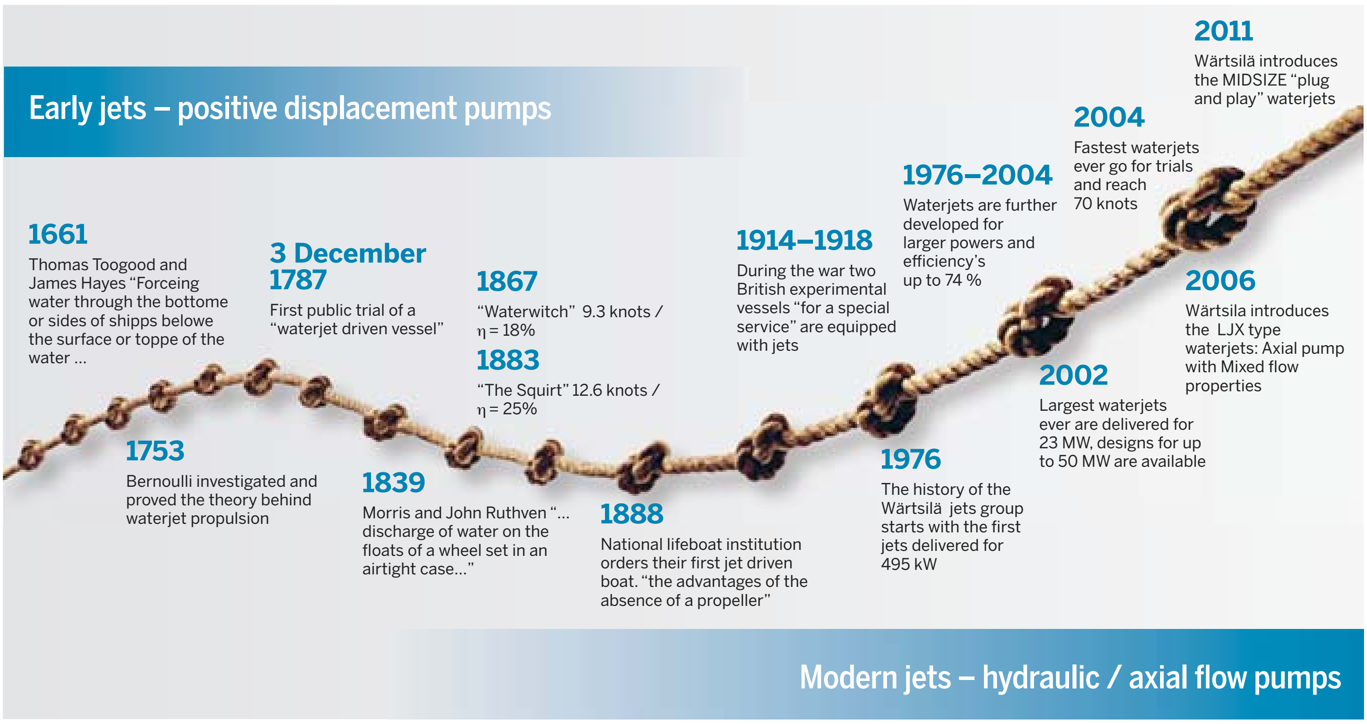
Currently, waterjets are mostly used in high-speed applications where conventional propellers are inefficient. Wärtsilä has been supplying waterjets for use in large vessels for more than 35 years. An axial-flow solution was introduced in 2006 and similar technology is employed in the company's midsize waterjet package concept.

The waterjet propulsion system was probably invented almost four centuries ago by David Ramseye [1]. In 1630, he stated in English Patent No.50 that he was able "to make Boates, Shippes and Barges to goe against Stronge Winde and Tyd". Three decades later in 1661, English patent No.132 was granted to Thomas Toogood and James Hayes for their invention of *Forceing Water by Bellowes [...] together with a particular way of Forceing water through the Bottome or Sides of Shipps belowe the Surface or Toppe of the Water, which may be of siguler Use and Ease in Navagacon.* While there is no doubt that this concept was based on a waterjet, they did not develop a working prototype. It was also not a high-speed device, and the competition consisted of modified Archimedes screws. Both this invention and subsequent developments in waterjet technology up until the 1980s is described in detail by Roy [2].

The extensive developments in high-speed vessels can in part be contributed to the application of waterjet propulsion systems. The stern-mounted waterjets in current use are based on the principles used in products built by the Italian manufacturer Riva Calzoni in 1932. In the 1950s, US Navy hydrofoil applications boosted their use, and this in turn led to the famous Boeing jetfoil (a passenger-carrying version was launched in 1974) →

Fig. 1 – The historical development of waterjet propulsion systems.



being powered by waterjet propulsors. The use of waterjets in commercial applications, however, only really started to grow after 1980 [3]. Figure 1 provides a historical view of events leading to current waterjet technology, with the basic development being driven by technology developed in Europe and applications involving high-speed vessels.

During the first decade of the 21st century, the diameter of waterjet units has increased to well above two metres with installed powers of up to 25 MW per unit. High-speed luxury motor yachts can now achieve speeds that are well above 65 knots (almost 120 km/hour) [4]. Waterjets can now in fact be considered a form of propulsion capable of operating successfully in sectors where conventional propellers are normally used. Improvements in pump technology have increased overall levels of efficiency, and the range of applications supported is a lot wider.

Waterjet components and operating principles

Waterjet propulsion systems consist of an inlet duct which guides water into the pump, an engine-driven impeller to raise the water pressure, guide vanes which support the impeller shaft and also reduce rotational losses, and a jetavator which directs the stream of water emerging from the pump to steer the vessel. The thrust resulting from the ejection of water by the pump is transmitted to the vessel through an inboard thrust bearing. The arrangement of these components in Wärtsilä LJX waterjet assemblies is shown in Figure 2.

Figure 3 is a simplified diagram of the inlet duct and pump sections showing the impeller, stator bowl and nozzle. Waterjet units are normally mounted on a vessel's transom. The stator bowl is specially designed to regulate water flow so that the pump and jet system can operate under optimum conditions. The acceleration of the mass of water flowing through the system results in a thrust force on the vessel:

$$\textit{Thrust} = \textit{Mass flow} * (V_J - V_I)$$

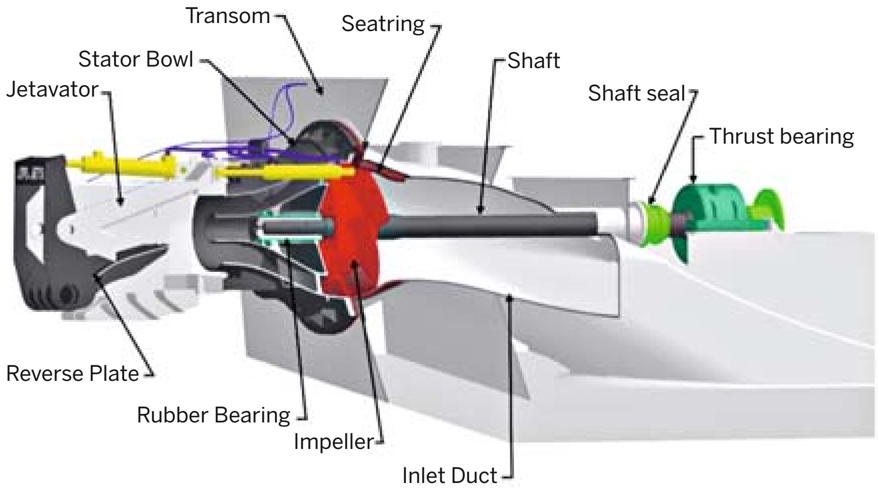


Fig. 2 – Waterjet components

Types of pump

Historically, pumps are classified by their specific speed, a number which is basically a ratio between flow through the pump and the delivered pressure. Typical pump outlet sections are shown in Figure 4.

Centrifugal pumps (shown on the left in Figure 4) convert a horizontal flow of water into a radial flow, deliver a relatively high pressure at small flows and have a low specific speed. In configurations with higher specific speeds, liquid flow through the pump becomes axial with larger flows being delivered at lower pressures.

The manner in which pump construction changes with specific speed is also shown schematically in Figure 4. In the axial-flow pumps on the right, the flow of water follows the line of the pump shaft. Power curves for different pump designs have different slopes and are shown in Figure 5.

The slope of the power curve indicates the extent to which the delivered power will be affected by changes in the pump's working point. This is an important aspect of performance when operating high-speed vessels. While the power absorption of an axial pump changes significantly with a change in flow, power absorption in a mixed-flow pump is relatively insensitive to changes in flow rates.

The power absorption curve for a typical FPP is also shown in Figure 5. As propellers operate at higher specific speeds than the axial pumps in waterjet assemblies, the slope of their power curves is even steeper. This in turn means that a relatively small change in flow results in a relatively large change in the level of power absorbed.

A detailed analysis of waterjet systems reveals that the pump best suited for vessels operating between moderate (25+ knots) and high speeds (up to 60-70 knots) is of the so-called "mixed flow" type.

Land-based pumps usually feature robust forms of construction and have relatively large diameters, which means they are heavy and unsuitable for use in propulsion systems. Also, the space available in a vessel's transom for installation is normally quite restricted,

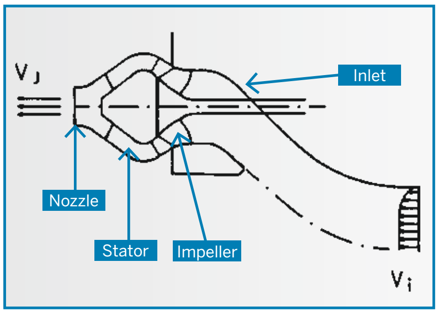


Fig. 3 – Cross-section of a waterjet inlet duct and pump section.

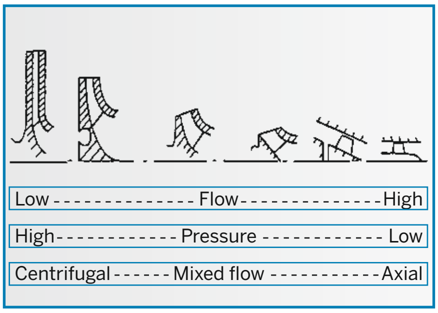


Fig. 4 – Pump outlet sections.

especially in vessels with high levels of installed power, and there is often the need to install a deck or swimming platform above external components of the waterjet assembly. Wärtsilä's new waterjet pump therefore offers the benefits of an axial pump design but has the required mixed-flow hydraulic properties, and maximum assembly diameters have been reduced significantly. The resulting propulsion solutions are also lighter and more cost-effective.

Comparison with FPP solutions

It is important to avoid confusing the behaviour of waterjet impellers with that of fixed-pitch propellers (FPP). As a propeller is located in the stream of water that passes around the vessel's hull, the effect of anything that reduces ship speed, such as headwinds or fouling of the hull, has an immediate impact on the propeller. If the propeller speed is maintained, the power demanded from the engines will increase, with the risk that they will be overloaded. For this reason, propellers are not designed for 100% MCR (maximum continuous rating) but for lower levels of power output, usually around 85% MCR.

As the impeller of a waterjet is not located in the water stream surrounding the hull, external factors that influence ship speed have only a small influence on flow through the pump. Together with the relatively flat power curve (Figure 5), power demand from the vessel's engines hardly changes. For this reason, the design of waterjet impellers is always based on 100% MCR.

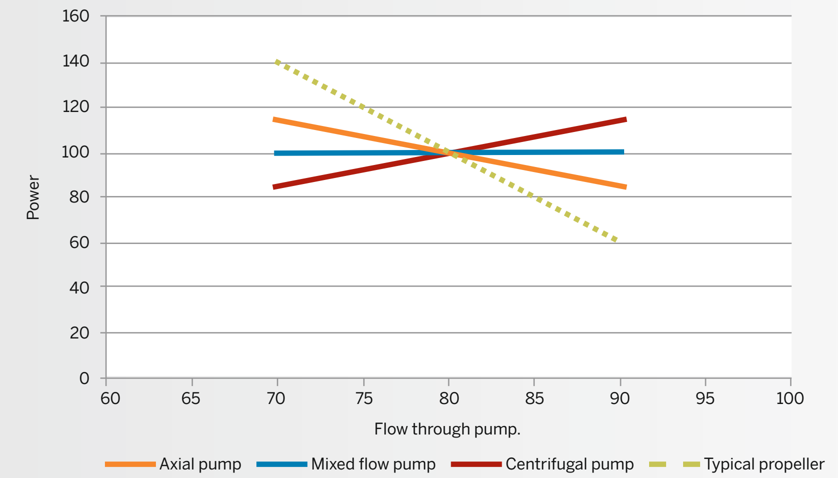
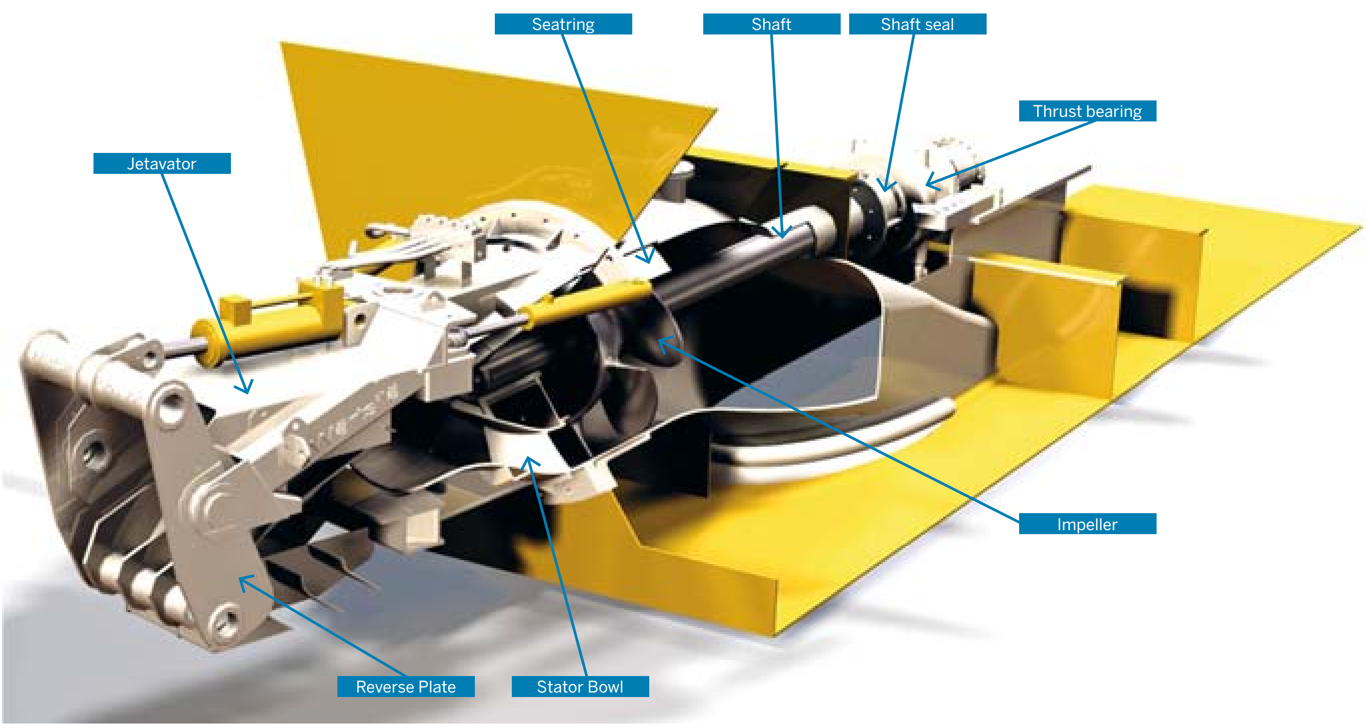


Fig. 5 – Power curves for different pump types. The dotted line is the power curve for a fixed-pitch propeller (FPP).

Suitable for both high-speed and low-speed applications

Waterjets are mainly used for high-speed vessels because at speeds higher than 25-30 knots, the amount of power required to propel the ship is lower than for other types of propulsor. Comparisons with other →

Fig. 6 – Wärtsilä Axial Flow Waterjet



types of propulsion system should always be made on the basis of the installed power requirement. While propellers can have better propulsion efficiencies, differences in ship design due to the required appendages (rudder, shaft struts) mean that the hull resistance is normally higher, and the propulsion power required is consequently larger than it would be if waterjets were installed. Rudders and conventional shaftlines can add as much as 10-14% to the bare hull resistance, while a waterjet propulsion solution entails no such effect.

Even though waterjets are the preferred propulsor for most high-speed ships being built today, they can also be successfully used in low-speed applications. Most cases involve situations where propellers would be considered vulnerable if a vessel is mostly sailing in shallow water, but fast patrol boats have also been converted from propeller propulsion to waterjet solutions to avoid situations in which their propellers are fouled by nets thrown overboard by smugglers or other vessels they are pursuing.

Waterjet-vessel interaction

Waterjets are usually located at the rear of the vessel in an area where the boundary layer in the flow of water along the hull is well developed. One consequence of this is that the average speed of the water entering the duct inlet is lower than the vessel speed. In an analogy with propeller solutions, the deficit is called the wake fraction, and it has a positive influence on overall efficiency as it lowers the average intake speed. An approximate figure for the wake fraction is 10%, which results in an increase in efficiency of approximately 5%.

Another interaction coefficient is the so-called thrust deduction. For propellers this is a well defined quantity, i.e. the increase in hull resistance caused by the altered flow conditions at the stern of the vessel. As both propeller thrust and resistance are quantities that can be measured, the resulting thrust deduction can be obtained from model-scale experiments.

In the case of waterjets, direct measuring methods do not exist. The flow through a jet is measured in model-scale tests and the theoretical wake fraction and thrust are then calculated. The difference between the (calculated) thrust and the resistance is however still called thrust deduction,

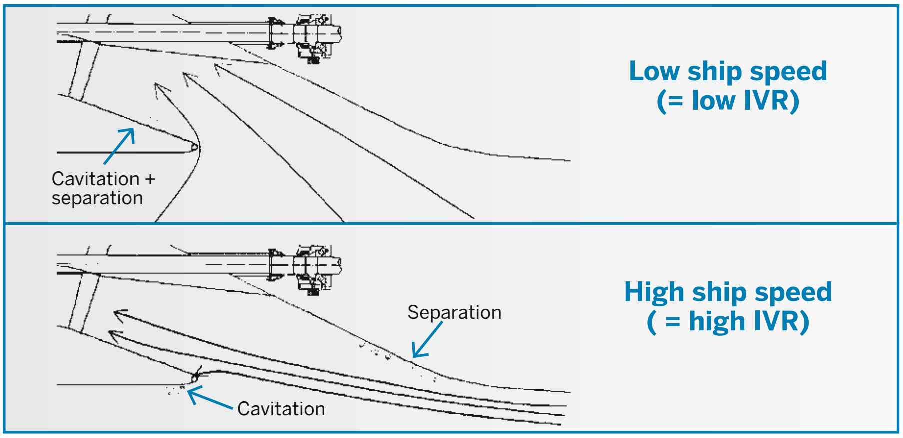


Fig. 7 – Water flow in the inlet duct

but basically it is a correlation coefficient. At large Froude numbers, it can even become negative (typically by a few percentage points), which means that less thrust is required to power the vessel.

Inlet design

Duct inlets are important components in waterjet installations. Power losses in the inlet section total 6-8%, and both the inlet design and its construction are critical. The correct balance has to be found between avoiding flow separation at the ramp and cavitation on the top of the cutwater, while minimising losses and creating a proper flow field for the impeller (see Figure 6).

Wärtsilä uses the StarCD CFD package to design and optimise waterjet duct inlets. This software has been extensively tested and offers reliable answers to most design questions. A typical case which highlights the excellent correlation between model tests and calculations of the velocity inflow field at the location of the impeller is shown in Figure 7.

Applications for waterjets

Waterjets are used in a broad range of applications, from small sports boats up to the largest megayachts and high-speed ferries. They are used by both commercial concerns and by government departments.

Types of vessel in which waterjets are used include:

- vessels with a high power density (large installed power in a relatively small ship)
- shallow-draft vessels such as landing craft
- high-speed vessels (30 knots+)
- hybrid propulsion vessels which combine good performance at low speeds with high (temporary) maximum speeds
- vessels used in life-saving operations

High-speed vessels often feature high levels of installed power and high power densities. Compared to an equivalent FPP solution, a waterjet propulsion solution is smaller and requires much less space, both inside and underneath the vessel. While a 5 MW propeller would typically have a diameter of 3.5 m, the diameter of an equivalent waterjet would be some 0.9 m. Currently, the largest power source connected to a 2180 waterjet (diameter 2.18 metres) is a gas turbine capable of delivering an extraordinary 26 MW.

Shallow-draft vessels such as landing craft often employ waterjet propulsion solutions. Not only does the absence of rudders and propellers under the vessel avoid the problem of colliding with the sea bottom, the integrated steering and reversing assembly, an integral part of the waterjet assembly, offers excellent manoeuvrability in shallow water.

The most common reason for using waterjets is to achieve high vessel operating speeds. Compared to conventional propeller solutions, the high internal dynamic pressure in a waterjet results in the propulsion system having a much higher efficiency at high speeds, with cavitation only setting at a much later stage. Waterjet efficiencies can be as high as 75% and speeds of up to 80 knots are possible. At such high speeds, conventional propeller solutions would suffer severe loss of thrust because of massive levels of cavitation.

Hybrid propulsion systems which employ both a CPP (controlled-pitch propeller) and one or more booster waterjets are employed in both yacht and navy applications. The resulting combination offers both efficient slow-speed operation using the propeller(s) and high-speed capability. Small navy vessels - such as corvettes - sail at slow speeds for 80% of the time and the efficiency of waterjets at slow speeds is poor. By combining the good performance of CPPs at low speeds and the thrust available from the waterjets at high speeds, hybrid propulsion systems are a perfect way of benefiting from the best of both worlds.

In life-saving operations, waterjets are a perfect propulsion solution because their rotating elements are fully protected, making operation safer both for people in the water and aquatic life. Waterjet propulsion has been used in lifeboats since the late 19th century and is nowadays widely employed.

Three market categories

The market for waterjet propulsion solutions can be divided into three segments – large, medium and small – each of which has its own needs and requirements. Large waterjets (4-40 MW per jet) are made of stainless steel and assembled by shipyards. Waterjets of medium size (1-4 MW per jet) are often made using aluminium, but a number of producers, including Wärtsilä, manufacture them out of combinations of stainless steel and aluminium. Wärtsilä offers a range of midsize 'plug and play' waterjet packages. Small waterjet assemblies are manufactured from aluminium and are usually available off the shelf at relatively low cost.

In terms of volume, large waterjets are sold in small numbers and are typically found in luxury megayachts and high-speed ferries. Large navy vessels with high design speeds also regularly feature large stainless steel waterjet assemblies. Waterjets of medium size have been widely used for many years in small fast ferries, in patrol boats, and in coastguard and crew supply vessels. The last of these categories is likely to experience increased demand as the number of wind farm installations in sea locations is expanding rapidly. Small waterjets are used in the widest range of applications - from small sports boats to amphibious vehicles, high-speed RIBs and small landing craft.

The Wärtsilä midsize waterjet package

Based on Wärtsilä's successful large axial waterjets, the focus of the new Wärtsilä Steering Reversing Frame midsize waterjet package is smaller vessels of 20-60 metres with installed power of 1-4.5 MW per shaft. Supplied in a competitive and easy-to-install package, the inlet duct is part of the scope of supply and delivered pre-assembled on a skid for direct 'weld-in' or 'bolt-in' installation in the vessel's hull, significantly reducing shipyard installation work and costs. As well as the drive line of the jet being fully aligned, auxiliary systems are mounted on the skid with all piping connections completed.

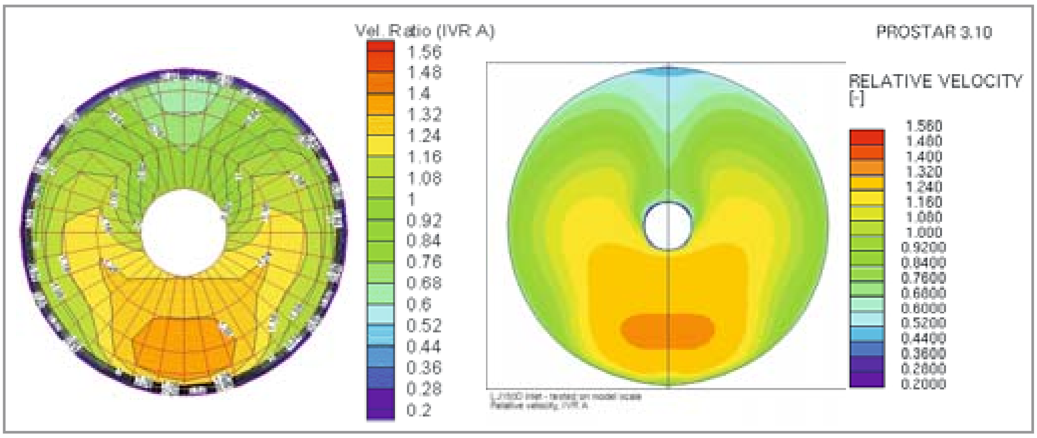
The key feature of the new waterjet package is the addition of the waterjet inlet duct to Wärtsilä's scope of supply. In large waterjet installations, the complex inlet duct shape has to be built by the shipyard in accordance with Wärtsilä's instructions. For large vessels this makes perfect sense – this element is typically more than 10 metres long and essentially part of the ship construction, so transporting it over long distances is not an economic proposition. Size and weight considerations also rule out significant pre-assembly. At smaller sizes, the inlet duct becomes more manageable, and full assembly and alignment of the waterjet and all auxiliaries such as hydraulic power packs, oil pumps and lubrication units, is both possible and practical. This adds value as it reduces shipyard requirements for machining, installation and alignment.

A full range of modular and midsize waterjets

Waterjet propulsion solutions do not resemble FPP solutions as the relationship between power absorption and ship speed does not exist. Their ability to deliver high levels of thrust means that they are the only choice for high-speed applications. Additional benefits such as the absence of appendages beneath the hull can also make them the preferred solution for special vessel designs.

Wärtsilä has a long history of supplying large modular waterjets to meet the special requirements of the demanding large-vessel market. In the equally-demanding midsize market where vessel design requirement are usually less application-specific, Wärtsilä's standardised waterjet packages offer a wide range of benefits.

Fig. 8 – Water velocity in the inflow field at the impeller (model tests on the left, computer simulation on the right).



REFERENCES:

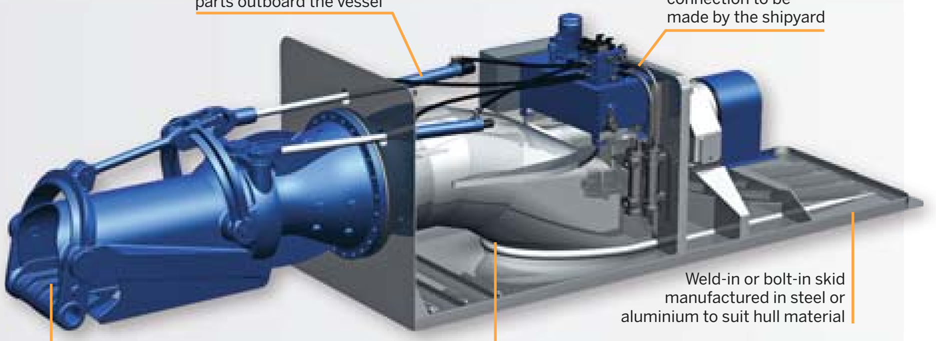
[1] & [2] Roy, S.M., 'The evolution of the modern waterjet marine propulsion unit', Proceedings RINA Waterjet Propulsion Conference, London, 1994

[3] Warren, N.F., & Sims, N.,'Waterjet propulsion, a shipbuilder's view', Proceedings RINA Waterjet Propulsion Conference, London, 1994

[4] Bulten, N. & Verbeek, R.,'Design of optimal inlet duct geometry based on operational profile', Proceedings FAST2003 conference Vol I, Session A2, pp 35-40, Ischia, Italy, 2003

THE WÄRTSILÄ MIDSIZE WATERJET CONCEPT

The Wärtsilä midsize waterjet packages offer shipowners and operators a number of unique features. These include an improved steering response, inboard hydraulic systems that remove the necessity to conduct outboard maintenance on sensitive hydraulic hoses, a simpler hydraulic power pack and thrust bearing lubrication set for reduced maintenance and greater reliability, and a high-performance pump design with a proven track record.



■ Pre-assembled waterjet packages
An efficient easy-to-install solution for jets between 1000 and 4500 kw

For shipyards, the Wärtsilä midsize waterjet 'plug and play' package offers reduced lead times in connection with design instructions and equipment information, and only a limited amount of engineering work required in newbuildings. It also offers minimised mechanical interfaces (one drive shaft connection and one cooling water connection), reduced yard machining and installation time as waterjet assemblies are delivered fully assembled and aligned, with no, or only limited commissioning required.

JETAVATORS PROVIDE IMPROVED STEERING RESPONSE

The core element in steering and reversing functions is the jetavator, which incorporates a secondary nozzle combined with a specially shaped primary nozzle exit. The focus is on both steering efficiency and responsiveness and the design process involves extensive CFD calculations and model-scale validations. The result is a steering device that does not obstruct water flow when the vessel is moving straight ahead, but responds quickly when steering with low losses and forward spray.

The reversing plate is controlled by an inboard hydraulic cylinder through a rod and yoke connection, a concept used and proven in several of Wärtsilä's modular (large) applications. As the steering cylinder is also mounted inboard, no hydraulic hoses or feedback cables are located outside the vessel hull. An additional benefit for ship designers is that the outboard section of the jetavator has a limited height requirement, so stern platforms can be as close to the water as practicable.

The basic shapes of the jetavator have been determined by CFD and testing, validated by FEM calculations, and optimised for production in co-operation with selected suppliers. The main components in the jetavator assembly are manufactured from aluminium.

STAINLESS STEEL GUARANTEES LONG-TERM PERFORMANCE

Stainless steel is used for fabricating all critical items in Wärtsilä midsize waterjets. One of these is the stator bowl, for which competing 'plug and play' jet packages use aluminium. The use of abrasion-resistant stainless steel conserves the carefully designed shape of the Wärtsilä stator blades, ensuring continued high levels of efficiency and corresponding fuel savings.

As the design is standard, the number of units is large and lead times are short, Wärtsilä uses castings for stator bowls in its midsize waterjets range. An additional factor is that the steering concept developed for midsize waterjets resulted in the stator bowl having a special shape that is best realised in a casting.

The selective use of stainless steel keeps the price of Wärtsilä's midsize waterjet package competitive, maintains vessel profits, increases vessel range and reduces environmental impact by delivering the best possible fuel efficiency.

OPTIMISATION FOR EACH VESSEL HULL

While the philosophy of delivering a 'plug and play' package that includes an inlet duct is not a new one, Wärtsilä's offering includes optimisation of the standard inlet duct form for each new vessel's hull. This customisation option within the standard midsize waterjet package guarantees high levels of efficiency in all hull forms. The optimised duct component is manufactured from aluminium plates, and the inlet has adequate stiffening elements to handle the forces generated by the waterjet unit.

The inboard thrust bearing is mounted on the inlet and is similar to that used in modular designs. The advantage is that lubricating oil is not close to the water, avoiding the risk of damage from water ingress and making inspection and maintenance tasks easier.

Auxiliaries are also installed on the inlet. A shaft-driven double pump handles the supply of oil to the hydraulic and lubrication systems, avoiding layout issues and shipyard engineering time when using a gearbox-driven PTO.

The Wärtsilä midsize waterjet package also includes machinery controls. As well as allowing flexibility in control system selection, this feature enables a full Factory Acceptance Test, reducing the need for a commissioning engineer.