Doha International Maritime Defence Exhibition and Conference
DIMDEX 2008, Qatar, March 2008

A Breakthrough in Waterjet Propulsion Systems

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ABSTRACT

Waterjets are common place in vessels needing to achieve speeds of 30+ kts where conventional propeller solutions are unable to overcome the associated issues of cavitation, which in turn can lead to thrust breakdown and material failure. Any vessel designed for high speed requires a low resistance and corresponding slender hull. Of course this is not enough, the propulsor needs to also be capable of accepting a high level of power and hence for a given diameter a high power density.

Wärtsilä identified the need for a more compact, performant waterjet installation simply because the design of the vessel dictates the maximum size of the waterjet transom flange diameter. Due to this constraint the operational envelope of a waterjet can be limited at speeds well below the designed top speed. For fast patrol boats and fast attack craft flexibility and good acceleration at patrolling speeds is one of the key performance indicators, however.

The task for Wärtsilä was clear but by no means easy as the mechanism by which the jet delivers enough thrust at top speeds (small inlet diameter and high power) is opposite to that for low patrolling speeds (large inlet and low power). By changing the pump geometry, Wärtsilä discovered a break through. The new pump is characterized by its axial geometry, whilst keeping the typical top efficiency of the commonly applied mixed-flow pumps.

Thanks to Wärtsiläs’ long experience in computational fluid dynamics (CFD) in waterjet applications, the performance could be determined through analysis of both the pump geometry and the inlet duct design.

This paper discusses the merits of the axial-flow pump geometry over that of mixed-flow and how it enabled Wärtsilä to deliver outstanding performance both in terms of the size of the installation and increased cavitation margins at patrolling speeds.

1 INTRODUCTION

The continuous development of new propulsion systems has resulted in both new challenges and new capabilities for navies and defence analysts. Use of high speed vessels for hostile activities necessitates the development of new types of vessels to counter the offensive. Consequently, the need for fast response craft will play an important role in future navy and coastguard fleets. They must be capable of quick deployment, rapid acceleration and above all capable of achieving top speeds of 40+ kts.

Until recently the conventional means of achieving such a vessel speed is to use fixed pitch propellers driven by high speed engines but the suitability of such is limited by the propeller efficiency at speeds above 30 kts coupled with inflexibility for manoeuvring at loitering and patrolling speeds. Increasingly, the deployment of waterjets in substitution of fixed pitch propellers is happening more and more, because they offer higher top efficiencies, improved control at manoeuvring speeds as well as improved loading on the engine throughout its torque map.

The typical operational zones of a waterjet installation are shown in the thrust diagram, as presented in figure 1. The design speed in this case is 45 kts. The available thrust at lower speeds is used to overcome the thrust at the hump-speed, which is common for planning vessels. However, the remainder of the available thrust can be utilised to increase the acceleration and manoeuvring performance of the vessel. For optimum operability of for example a patrol vessel, both the top speed design condition as well as the performance at manoeuvring speed should be addressed.

The performance breakdown due to cavitation (denoted in figure 1 as cavitation limit) is governed by the allowable power-density (P/D^2) of a waterjet installation. As a consequence, the minimum required pump diameter is settled for given installed power, based on this criterion.

* Wärtsilä Propulsion Netherlands is the manufacturer of Lips Waterjets

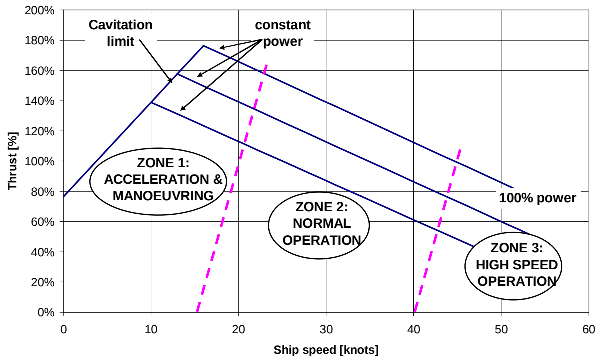

Figure 1: Thrust diagram with operational zones of waterjet installation

Improvement of the acceleration and manoeuvring performance of the vessel can thus be achieved with larger waterjet installations. However, the increased weight and required transom area are two significant drawbacks of larger installations.

Wärtsilä has found another solution to improve low speed performance with the development of a new waterjet pump type with improved cavitation margins.

The pump design has been used for the development of the waterjet series, denoted as WLD-type. With this pump, improved acceleration and manoeuvring is achieved whilst keeping the size and weight of the waterjet installations comparable to current installations. Of course, the performance improvement can also be utilised to reduce the size and weight of the installation significantly, whilst keeping the performance of the installation at the same level.

To visualise this improvement more clearly, some example cases will be presented in this paper. In these cases the performance of the new pump type will be compared to the well-known Lips Jets 6-bladed E-type waterjet. This type has been in service on many vessels over the last 10 years.

First the theoretical background of the development of the new pump and the performed numerical analyses will be discussed in more detail.

2 DEVELOPMENT OF NEW AXIAL-FLOW PUMP

From literature it is known that the highest attainable pump efficiencies are obtained with mixed-flow pumps in general. Both axial and centrifugal pump types do not reach this high level of more than 90% pump efficiency. However, for the development of a new axial-flow pump this high efficiency level has been set as a constraint. Though this seems to be in contradiction with common experience, it is shown to be possible for waterjet propulsion applications. Conventional pumps are designed to produce static head (pressure), whereas a waterjet installation should produce momentum (high velocity at nozzle exit). This subtle difference between the two gives some additional design space to design a pump with axial-flow *geometry* and mixed-flow *performance*.

Figure 2 shows an overview of the geometry of conventional pumps as function of the specific speed. This empirical relation between the geometry of the pump and the specific speed is based on decades of pump design experience (see for example: Stepanoff, 1957; Wislicenus, 1965; Gülich, 1999). The specific geometry of a pump can be expressed with the specific diameter of a pump. Specific speed and diameter of a pump are defined as:

$$N_s = n \cdot \frac{\sqrt{Q}}{(gH)^{3/4}} \tag{1}$$

$$\delta = D \cdot \frac{(gH)^{1/4}}{\sqrt{Q}} \tag{2}$$

where n is the rotational speed, D the diameter of the pump, Q the flow-rate and H the head.

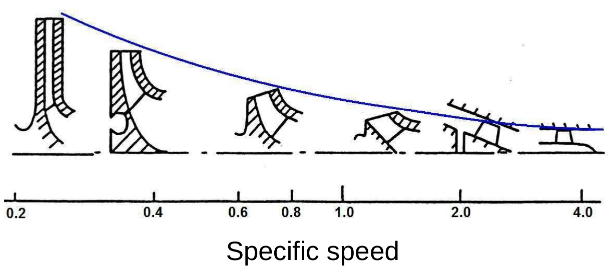

Figure 2: Pump geometry as function of specific speed

Figure 3 shows the empirical curve of the specific diameter, based on figure 2 and some typical waterjet pump types. It can be seen that the conventional waterjet types are in agreement with the empirical pump design rule.

However, the newly developed axial-flow pump deviates significantly from this line. The specific speed of the new pump is of the same order as the current 6-bladed E-type. On the other hand, the specific diameter is close to the older 3-bladed Lips-Jets D-type pump, which had the characteristic axial outline as well.

Summarizing: the design criteria: axial flow dimensions (specific diameter) and mixed-flow performance (specific speed) can be recognized clearly in this diagram.

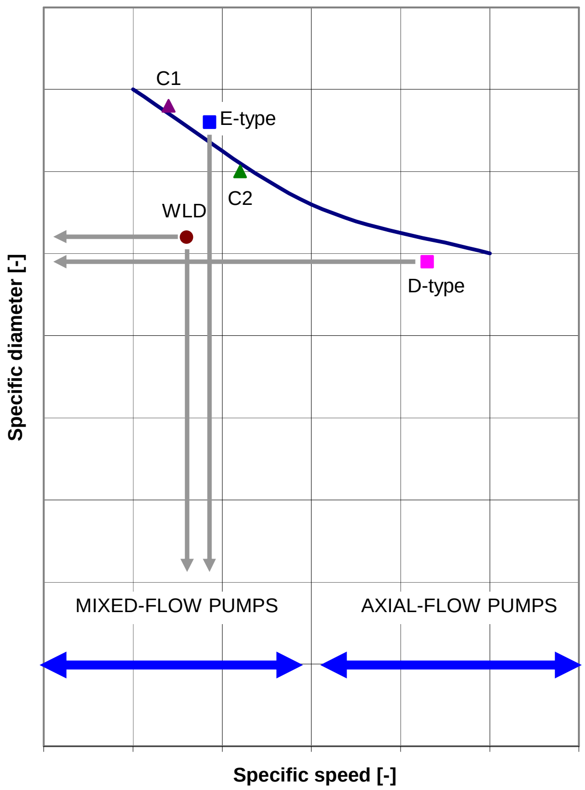

Figure 3: Cordier diagram with conventional and new waterjet pumps

3 NUMERICAL ANALYSIS OF PUMP PERFORMANCE WITH RANS-CFD

Performance of the pump has been determined both experimentally and numerically. Measurements are carried out at different research institutes over the world. The experimental program contained performance measurements and cavitation tests among others.

3.1 Background of numerical method

The numerical analysis of the pump performance is based on Computational Fluid Dynamics (CFD) simulations. The method is based on the Reynolds-Averaged Navier-Stokes (RANS) equations, which take viscous flow effects into account.

The geometry of the complete waterjet unit (viz. pump impeller, stator bowl and nozzle), has been included in the numerical domain. The clearance between the pump impeller and the stationary housing has been modelled as well.

The numerical domain is meshed with hexahedral cells, based on a multi-block approach. This method ensures good control over the quality of the cells near the walls, in which the effects of the boundary layer development are modelled. The complete mesh of the pump unit consists of about 1.46 M cells. Figure 4 shows a 3D view of the mesh, as used in the numerical simulations.

Effects of turbulent flow are captured with the standard k-ε turbulence model. This model is utilised at the authors' company for many years. Implementation of the body forces due to rotation of the impeller is based on the quasi-steady Multiple-Frame-of-Reference method. In this way the impeller is frozen at a certain fixed angular position. This method has been used before for the calculation of the performance of the E-type waterjet pump, which is described in detail in the PhD-thesis of Bulten (2006).

The commercial CFD code also provides a fully transient moving mesh capability, which moves the impeller mesh every time step in accordance with the angular speed of the pump. This method is required for detailed analysis of the rotor-stator interaction forces, for example. Since this method requires significantly more computational effort and is not needed for the purpose of calculating pump performance indicators like head and efficiency (Bulten & Van Esch, 2007), it is not used for the numerical analyses described in this paper.

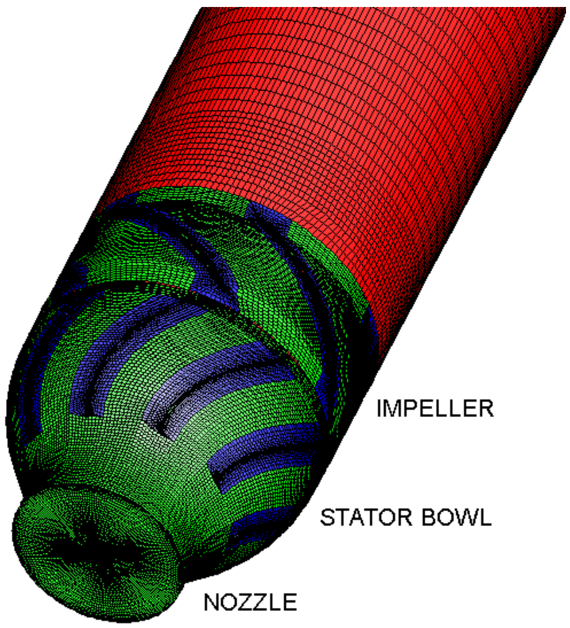

Figure 4: 3D view of WLD-pump mesh

3.2 Pump performance

The performance of the pump is evaluated by means of the pump head H and the pump efficiency η, which is defined as:

$$\eta_{pump} = \frac{\rho g H Q}{T \Omega} \qquad (3)$$

where T is the shaft torque and Ω the angular shaft speed.

Figure 5 shows the pump performance curve for the axial-flow pump. Both the experimental and the numerical data are presented in this graph. The pump head and efficiency at the design flow rate are used to show the values in normalised representation (H/H_design, Eta/Eta_design).

From this diagram it is concluded that the agreement between measured and calculated values is good for both the head and the pump efficiency. The agreement is found not only at the design point but also for the complete range of flow rates in which the pump is operated.

This proves that the numerical approach which is employed during the development phase gives performance predictions, which are as accurate as model scale performance tests. This is in agreement with expectations, since similar levels of accuracy have been found for other waterjet pumps in the past, using the same software and the same numerical approach (Bulten *et al*, 2006).

The benefits of the use of the numerical method are found in the increased flexibility during the development phase. Since there is no need to produce scale models for each geometry variation, a significant reduction in both time and cost is achieved.

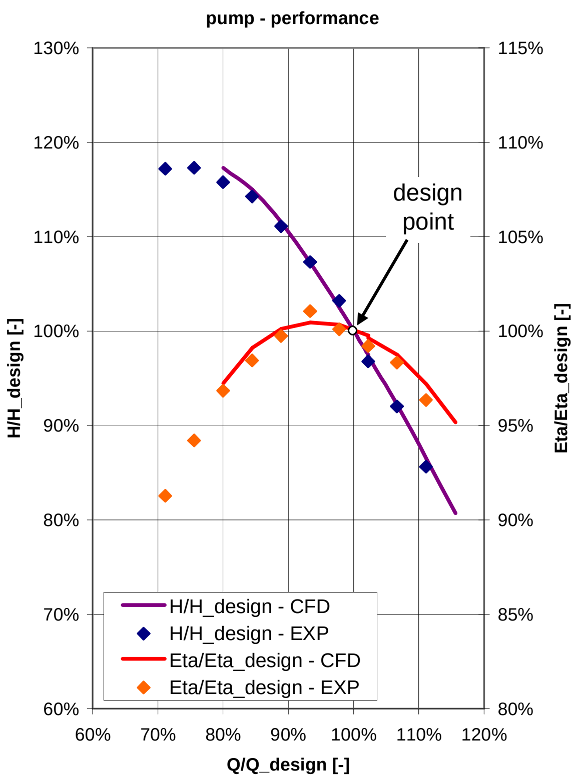

Figure 5: pump performance diagram for WLD-pump based on model scale measurements and numerical analyses with RANS-CFD

4 COMPARISON OF MIXED-FLOW AND AXIAL-FLOW PUMP DESIGNS

The performance of the new pump type will be compared to the existing E-type for three different cases. The LJ-160E with an inlet diameter of 1600 mm is taken as reference installation in all three cases.

First, the optimisation of minimum transom flange diameter is reviewed. In this case the requirements for the cavitation margins are kept identical for both pump types.

In the second case, the waterjet input parameters at the design point, viz. power and RPM, are kept constant. The requirement of identical RPM for both installations determines the size of the new pump type. Change in pump type may result in smaller installation or improved cavitation margins, or both.

The third comparison is based on the maximum allowable power, which is based on the mechanical limits. This selection criterion can play an important role for high powered displacement vessels and other vessels which do not have the high hump resistance.

4.1 Comparison of transom flange diameter for identical cavitation margins

The first case, which is analysed, is based on identical cavitation performance for both pump types. This will result in a smaller installation when the axial pump type is selected. This enables a reduction of hull transom width, which can be beneficial for the overall hull performance.

Selection of both waterjet types for identical installed power and cavitation margins, results in a mixed-flow E-type with an inlet diameter of 1600 mm and an axial-flow WLD-type with an inlet diameter of 1570 mm. Though the reduction in inlet diameter is rather limited, the effect of the size reduction is much more pronounced when the transom flange diameters of both installations are compared. The outer diameter of the E-type is 2700 mm, which reduces to 2010 mm for the axial pump, as shown in figure 6. This is a reduction of about 25%.

4.2 Evaluation of cavitation margin increase for identical performance at design condition

The second case is based on two installations with identical operational condition of the pumps (power and RPM). This comparison shows the possible improvement of cavitation margins for a given engine/gearbox configuration. Thrust diagrams for both waterjet types (LJ160E and WLD-1710) are presented in figure 7.

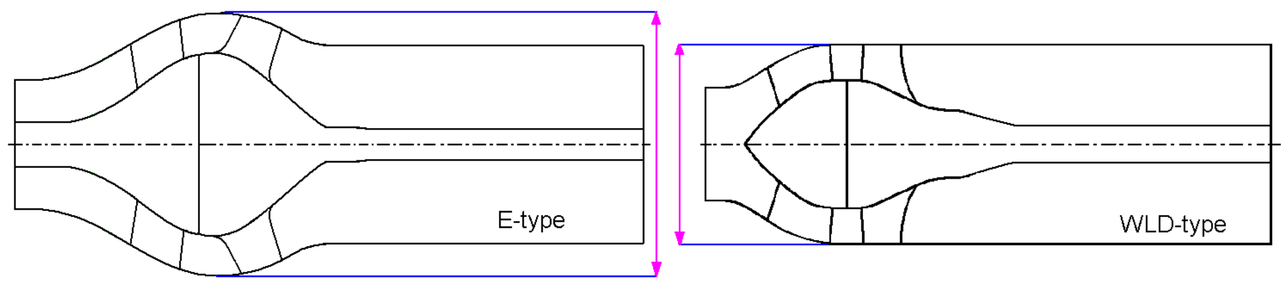

Figure 6: comparison of transom flange diameter for identical cavitation performance: mixed-flow LJ160E (left) and axial-flow WLD-1570 (right)

The performance at the design point (ship speed is 45 kt, thrust is 100%) is identical for both installations, which proves that both installations operate at the same efficiency.

It is shown that the cavitation margins improve significantly when the axial pump is selected. The improvement can be expressed in an additional margin against cavitation of about 6 knots. This gain in cavitation margin can enhance the performance of a vessel significantly in off-design condition; for example operation with a reduced number of engines.

The performance at manoeuvring speeds, indicated in figure 1 as zone 1, increases significantly. At a ship speed of about 15 knots, the available thrust increases with at least 30%, due to the improved cavitation margins. This gain in available thrust can be utilised to enhance the acceleration performance of the vessel significantly.

In addition to the improved hydrodynamic performance, the diameter of the transom flange will reduce by 17%.

4.3 Maximum allowable power based on mechanical strength criteria

For high speed installations the critical selection criterion for the waterjet size can change from cavitation margins to mechanical strength limits. The maximum allowable power density P/D^2 of a waterjet installation governs the actual size of the installation for given installed power. In the expression for the power density, the diameter is based on the inlet size.

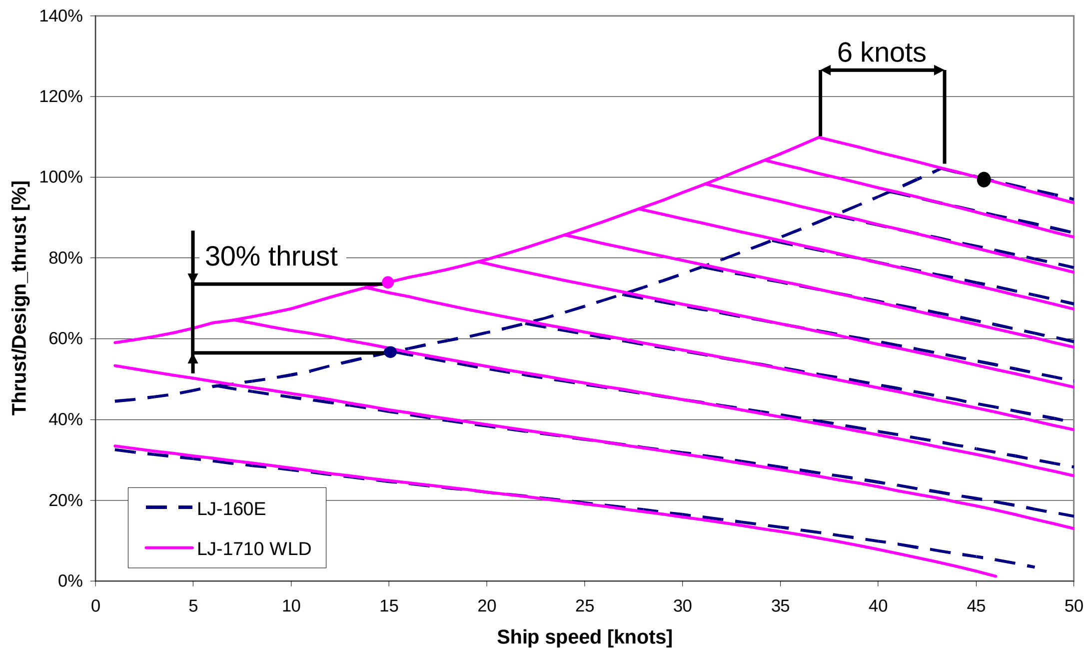

Figure 7: comparison of thrust diagrams for mixed-flow LJ160E and axial-flow WLD-1710 for identical power and pump RPM at design point of 45 kts

Figure 8 shows the maximum allowable power as function of the transom flange diameter for both pump types. The maximum allowable power for the LJ160E has been taken as a reference value.

As shown in figure 6, the ratio between the inlet diameter and the transom flange diameter depends on the waterjet type. Reduction of the diameter ratio is beneficial for the allowable power for given transom diameter.

The figure shows that the new pump design can absorb about 16% more power for the same transom flange diameter. It is also shown that the minimum required transom diameter reduces from 2.7 to 2.5 m for the same power. This difference can be translated in a reduction of the required transom width of about 8%.

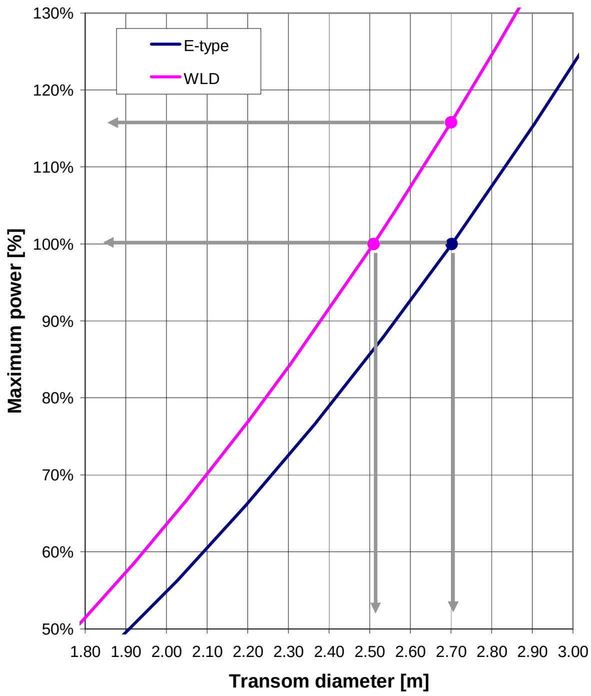

Figure 8: maximum allowable power as function of the transom flange diameter based on mechanical strength criteria

5 CONCLUSIONS

- The development of a new axial-flow pump type for a waterjet propulsion system has resulted in two new pump types, denoted as LJX and WLD.

- The performance of the new pump has been determined both experimentally and numerically. The results of both methods agree very well for both pump head and efficiency.

- Though the geometry of the pump is similar to an axial-flow type, the top efficiency of a mixed-flow pump is still maintained.

- For a waterjet selection based on cavitation margins, a transom flange diameter reduction of 25% can be obtained with the axial pump. If the selection is based on maximum allowable power, which is applicable for high speed applications (>60 kts), a reduction of about 8% can be achieved.

- The selection based on identical operating condition, e.g. power and RPM, results in an installation with a 17% smaller transom flange diameter. Moreover, the cavitation margins are improved significantly. A typical increase of about 6 knots at full power can be obtained. At lower speed, for example around the hump speed, an increase of thrust of more than 30% is found.

- Evaluation of the maximum allowable power based on mechanical strength criteria learns that the new axial pump can absorb about 16% more power for identical transom flange diameter.

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