DYNAMIC POSITIONING CONFERENCE
September 28-30, 2004

SESSION: Thrusters

Minimization of Thruster Dimensions for DP Systems

Martijn van Rijsbergen
MARIN (Netherlands)

Henk Terlouw
HRP Thruster Systems (Netherlands)

Cees Leenaars
Dockwise (Netherlands)

Return to session directory

Abstract

The current paper focuses on the minimum thruster dimensions and the prospects this gives for the design of thrusters for DP systems. It reports the results of a design study in which a thruster with a special ducted propeller has been designed and tested at model scale.

Van Rijsbergen and van Terwisga [1] have shown that the current rules of thumb which are used to determine the minimum diameter of the thruster's propeller correspond approximately with the conditions where propeller cavitation starts to have negative effects on the thruster's performance. However, if sufficient power is available and special attention is paid to the design of the propeller and the thruster housing, a decrease in propeller diameter of about 30% can be achieved. Using these results, a comparison is shown of the geometry and dimensions of a standard thruster and a thruster with minimized dimensions.

Introduction

The dimensions of azimuthing thruster units of a certain power range are, next to the type of mounting (e.g., well mounted or retractable) and the drive system (e.g., diesel or electric), largely determined by the selected propeller diameter. A decrease of the thruster unit dimensions at the same thrust output offers a number of advantages such as a more flexible allocation of the thruster unit in the vessel and fewer limitations in shallow water operations. A disadvantage is the lower efficiency, which implies a higher power demand at the same thrust output and hence a larger drive system.

For a thruster manufacturer, the higher power demand at a smaller propeller diameter raises the question about the maximum allowable power density of the propeller. In order to avoid risk of vibrations and erosion, commonly accepted maximum values of this power density are used, together with a maximum tip speed criterion to determine the minimal propeller size in an early design stage. These dimensional criteria are easy to use, and if they are kept constant for a whole thruster range, the (dimensional) thrust-power ratio also remains constant. These aspects are an advantage in the design of multi purpose thruster systems for which a good efficiency is important, but give little support in the search for the minimum propeller diameter.

In order to explore the physical background of the minimum propeller diameter for a certain thrust output (maximum thrust density without power limitations), several methods have been reviewed and compared in a universal non-dimensional form in [1].

The objective of the current paper is to investigate and quantify the effect of the propeller design on the minimum propeller diameter and the required power input of DP thrusters by model tests in the bollard pull condition. Further, the overall dimensions and costs will be evaluated in comparison with a conventional thruster.

Maximum thrust density

In Figure 1, the effect of cavitation on the required propeller diameter (at a constant thrust) and the delivered thrust (at a constant diameter) as a function of the tip speed is sketched by black lines, the theoretical non cavitating condition is shown by grey lines for reference purpose.

When the tip speed of a certain propeller is increased in the bollard pull condition, the thrust increases first with the square of the tip speed. Then, cavitation develops on the propeller blades and starts to influence the propeller's characteristics such as thrust, power and efficiency. The point where the thrust is decreased by 2% relative to the non cavitating condition is designated in the current paper as thrust influence. As shown in Figure 1, the thrust continues to increase with the rotation rate, but only with a smaller gradient. When the rotation rate is even further increased, the cavitation area will generally grow from the tip to the root until it covers the whole blade (supercavitation). At this point, the thrust has reached its maximum value and will be designated further on as the point of thrust breakdown. When the rotation rate is increased further, cavitation fills the whole propeller disk which causes the thrust to decrease. This process is described in detail by Prishchemikhin [2].

In the same way, the effect of cavitation can be shown on the required propeller diameter at a constant thrust. Theoretically, the diameter decreases in the bollard pull condition with $1/\sqrt{(V_{tip})}$, but due to cavitation, the diameter needs to be larger. At the point of thrust breakdown, a minimum in the diameter is reached.

In Figure 2, this process is sketched in a non dimensional cavitation diagram. Instead of dimensional quantities such as thrust (T) and propeller tip speed (V_{tip}), non-dimensional quantities such as thrust coefficient (K_T) and cavitation number (σ_n) are used. This diagram is mostly used by propeller designers to indicate several forms of cavitation inception. In the current paper, it will also be used to define the design point of the propeller and to present the results.

When the propeller rotation rate is increased in the bollard pull condition, the cavitation number decreases at a constant thrust coefficient (follow the solid line down). First cavitation inception will occur. When the rotation rate is further increased, the amount of cavitation increases and starts to influence the thrust. Finally, thrust breakdown occurs, which is defined in this diagram as the point with the highest K_T/σ_n value. In the non dimensional diagram this is the point of contact of the thrust coefficient curve and its tangent which passes through the origin.

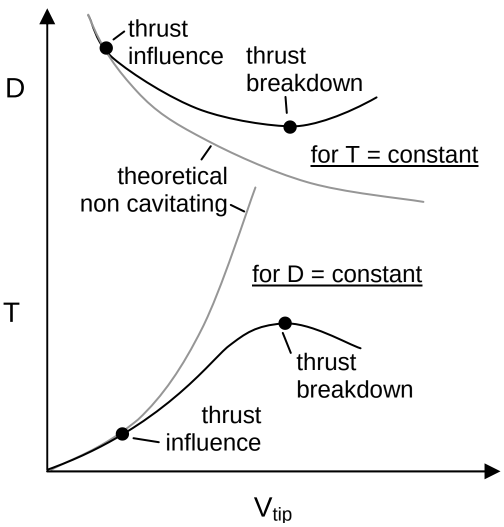

Figure 1 Effect of cavitation on propeller diameter and thrust

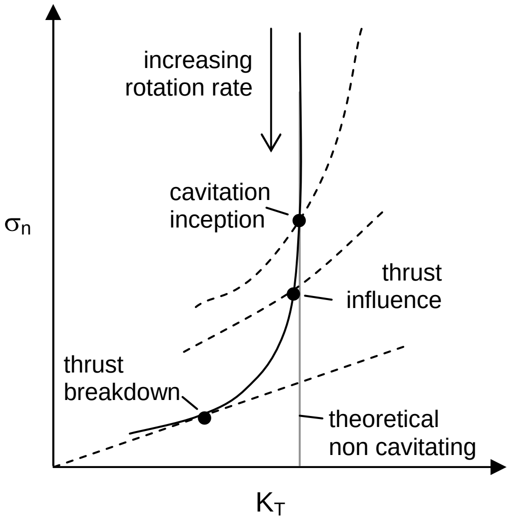

Figure 2 Non-dimensional cavitation diagram

Equation (1) shows that a high thrust density (T/A_0) is equivalent with a high K_T/σ_n ratio.

$$\frac{T}{A_0} = \frac{8 \cdot (P_0 + \rho g h - P_v)}{\pi} \cdot \frac{K_T}{\sigma_n} \tag{1}$$

In the region between thrust influence and thrust breakdown, the efficiency of the propeller decreases and the risks of cavitation induced vibrations and erosion gradually increase. Thrusters which are used for DP generally do not have such stringent requirements with respect to efficiency, cavitation and vibrations as thrusters which are used for main propulsion because they do not operate continuously at their maximum capacity. Nevertheless it is better to avoid this region as much as possible and to focus on the delay of the thrust influence by improving the propeller and thruster design. A first step in doing this is to map the propeller design space.

Propeller design space

Being in search for the maximum thrust density, first three propeller concepts were evaluated on their maximum thrust density in a preliminary design study. The choice for a ducted propeller was not self-evident because in [1] it was shown that for open propellers thrust breakdown occurs at a higher thrust density than for ducted propellers. On the other hand, the point of thrust influence for conventional

open propellers occurs at a lower thrust density than for ducted propellers. Next to an open propeller, two types of ducted propellers were investigated: one with a normal accelerating nozzle (by which the flow through the propeller disk is accelerated) and one with a decelerating nozzle.
The evaluation was carried out using MARIN's lifting surface program ANPRO in combination with pre- and post processing based on semi-empirical models [1]. For each propeller concept the rotation rate was increased at a constant propeller diameter. A limit was drawn at the point where extensive cavitation could no longer be avoided by changing the propeller design. Comparison of these design limits showed that the open propeller and the propeller in an accelerating nozzle had the best and almost equal potential for reaching a high thrust density. Since the propeller in an accelerating nozzle has a 60 to 70% higher efficiency, expressed in the merit coefficient (η_E) than the open propeller, this propeller concept was chosen to continue the study with.

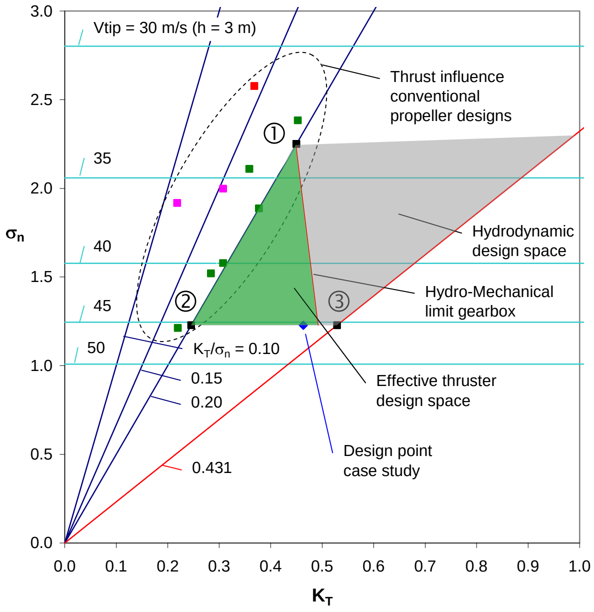

Figure 3 **High thrust density design space for thruster with ducted propeller**

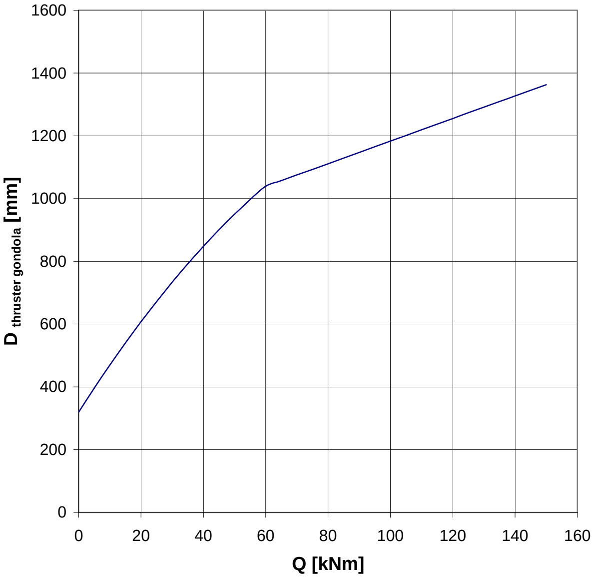

Figure 4 **Thruster gondola diameter versus propeller shaft torque**

The design space is shown in Figure 3 by a non dimensional K_T-σ_n diagram. Lines of constant tip speed and non dimensional thrust density (K_T/σ_n) are shown for reference purpose. Conventional designs are located in the region with K_T/σ_n values below 0.20 which corresponds approximately with a power density of 400 kW/m^2 and $\eta_E = 1.0$, see [1].
Based on [1] it is assumed that the limits of the hydrodynamic design space are formed by lines of constant K_T/σ_n and constant cavitation number (σ_n). From the preliminary propeller design study two values were derived: $\sigma_n = 1.23$ and $K_T/\sigma_n = 0.431$. Beyond these limits, it is expected that cavitation induced thrust influence or erosive forms of cavitation can no longer be avoided by changing the propeller design. The total shaded area indicates the hydrodynamic design space for ducted propellers with a high thrust density. The numbers indicate the design points of several propellers. Design point 1 is a propeller with common tip speed and thrust density and serves as a reference. Design point 2 is a propeller with maximum tip speed and design point 3 is a propeller with both maximum tip speed and thrust density. The difference in thrust density at which thrust influence occurs between point 1 and 3 is more than a factor two. This suggests that also a significant increase in maximum thrust density can be made by making a special propeller design.
The hydrodynamic design space is further narrowed down by specific mechanical limits for thrusters. One such a limit is formed by the diameter of the under water gearbox (gondola). This diameter increases with increasing propeller shaft torque because of strength requirements in the crown wheel.

HRP conducted a study in which first a relation between the propeller shaft torque and outer diameter of the thruster gondola was developed, see Figure 4. With this relation, a thruster size study was conducted in which 8 design points within the hydrodynamic design space were evaluated for two approaches: a constant thrust of 20 tons and a constant diameter of 2 m. The results of the study showed that the gondola/propeller diameter ratios (Dg/Dp) became too large for design points with relatively large thrust and torque coefficients. Based on maximum gondola/propeller diameter ratios used in current pods and thrusters, this ratio was limited to 0.45. Higher ratios will increase the gondola resistance beyond proportions and therefore decrease the total thrust of the thruster too much. In this way a new combined hydrodynamical/mechanical limit was formed. This limit is showed in Figure 3 as a red line. Due to the dimensional origin of this limit, the intersection with the line of minimum cavitation number (maximum tip speed) shifts towards left with increasing design thrust.

Thruster design

Heading towards an actual thruster design, first the pros and cons of a pushing and pulling propeller configuration were evaluated. Based on preliminary design calculations with a pushing propeller with a tip speed of 45 m/s, it was concluded that the erosion and vibrations would become too large because of the wake field of the thruster strut. A thruster with a pulling propeller would have less erosion and a lower risk of vibrations because of the favorable wake field. Damage to the strut because of erosion should be prevented by using a wear plate. The expected higher steering torque is handled by increasing the steering drive power and extending the strut more aft, balancing the moment caused by the nozzle in a cross flow condition.

A thruster with a pulling propeller is therefore chosen as a starting point in the thruster design. Further, choosing a bollard pull thrust of 20 tons at a propeller diameter of 1.41 m and a rotation rate of 614 rpm places this thruster design in the lower right corner of the effective design space, see Figure 3.

A standard MARIN 19A nozzle was used as a good compromise between thrust efficiency and diameter. A propeller with a large blade area ratio ($A_E/A_0 = 0.98$) was designed with the objective to reduce cavitation as much as possible using highly cambered sections which were optimised for cavitation inception. Special attention was paid to the streamlining of the thruster housing. For a design power of 1636 kW it turned out that the gearbox/propeller diameter ratio could be reduced to 0.40. The resulting thruster design is presented in Figure 5. The calculated bollard pull efficiency is 9.0 kg/hp or $\eta_E = 0.94$. It has to be noted here that an efficiency expressed in kg/hp is sensitive to the loading of the propeller and the non dimensional η_E is not.

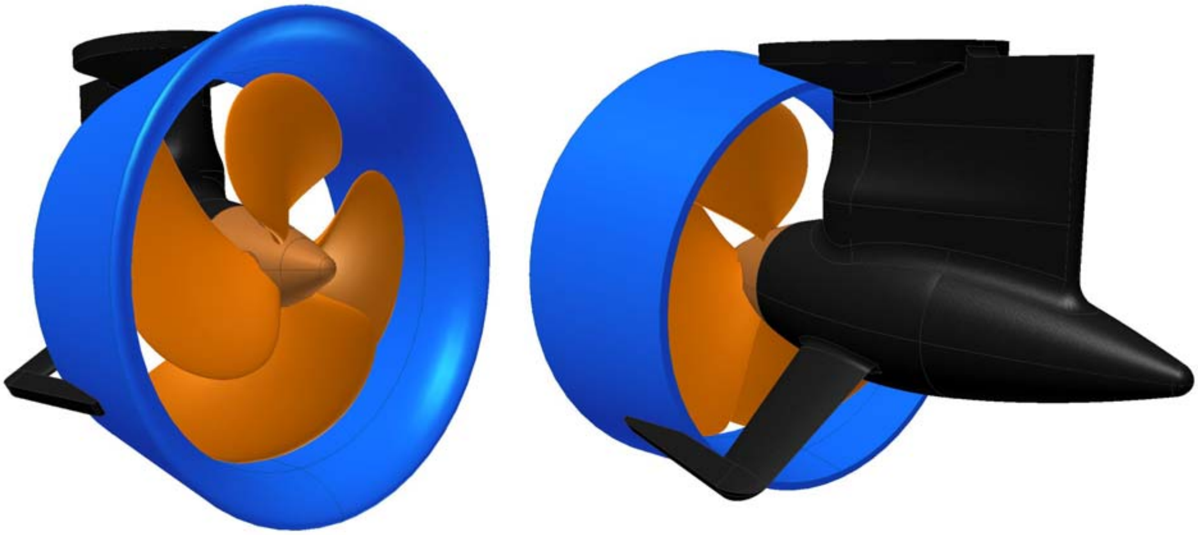

Figure 5 High thrust density thruster

Model tests

A verification of the design objectives has been made by conducting thrust and power measurements as well as cavitation observations at a model scale of 1:5.875. Conformation to a standard model propeller diameter of 240 mm enabled the use of a stock nozzle model and the use of a stock Ka 4-70 model propeller for reference purposes during the cavitation tests. This four bladed Ka propeller with $A_E/A_0 = 0.70$ is commonly used in standard thrusters.

Open water characteristics

The designed thruster was first tested in open water condition in the deep water towing tank of MARIN. A remarkable result is that between the bollard pull condition ($J = 0$) and $J = 0.4$, the unit thrust equals almost the sum of the propeller and nozzle thrust. Apparently the stator effect of the three struts (main and 2 side struts) balances the resistance of the thruster body. Further, the nozzle thrust is relatively small which is thought to be caused by the unfavourable interaction with the thruster gondola in this pulling configuration.

In the following discussion of results, the thrust is always defined as the thrust delivered by the total thruster unit. Without the influence of cavitation, a full scale bollard pull thrust of 20 tons is reached at a rotation rate of 600 rpm and a propeller shaft power of 1718 kW. In terms of efficiency this results in 8.6 kg/hp or $\eta_E = 0.89$. In the sailing condition a maximum efficiency of 46% is reached. The 5% loss in efficiency relative to the design objective is thought to be caused by the small thrust of the nozzle.

Cavitation characteristics

The cavitation tests were conducted in the large cavitation tunnel of MARIN. The test section measures 0.9 x 0.9 x 4.0 m. For both the designed propeller and the Ka 4-70 propeller, cavitation observations were made and thrust and torque decrease as a function of the cavitation number were measured. The tested conditions range from non cavitating to somewhat above the design tip speed and from the bollard condition to $J = 0.3$.

Observations

Figures 6 and 7 show the cavitation appearance on the Ka and the design propeller near the bollard pull condition ($J = 0.12$) at $\sigma_n = 2.5$ (Vtip = 32 m/s). The full scale propeller diameter is 1.41 m.

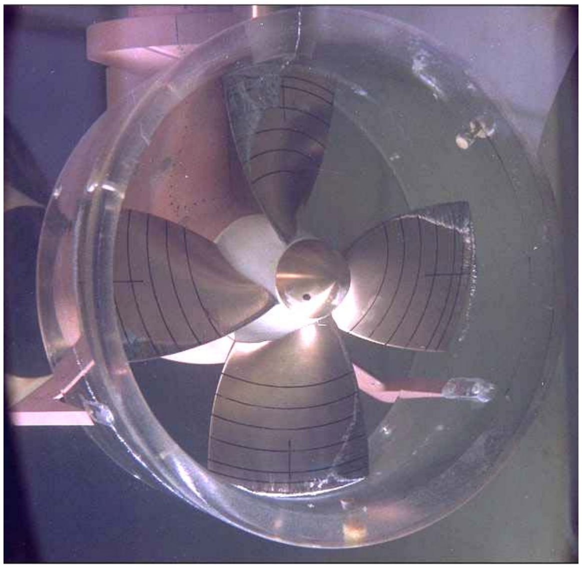

Figure 6 Thruster with Ka 4-70 propeller at T = 11.1 tons ($K_T = 0.510$)

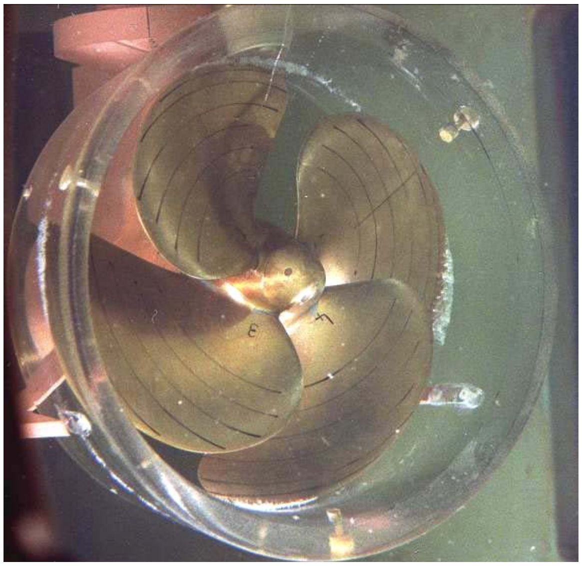

Figure 7 Thruster with design propeller at T = 9.4 tons ($K_T = 0.436$)

Figure 6 shows that at this condition with a tip speed of 32 m/s, the cavitation on the blades of the Ka propeller is limited to sheet cavitation in combination with a small tip vortex. The design propeller shows no sheet cavitation, only some cavitation in the tip clearance area. The difference in thrust is caused by the difference in virtual pitch of the two propellers.
Both figures show the presence of a cavitating propeller hull vortex (PHV). It is assumed that this vortex is strongly enhanced by tunnel wall effects, therefore it is expected that this will occur only at much higher tip speeds at full scale.
Figures 8 and 9 show the cavitation appearance on the Ka and the design propeller near the bollard pull condition (J = 0.12) at $\sigma_n = 1.5$ (Vtip = 42 m/s).

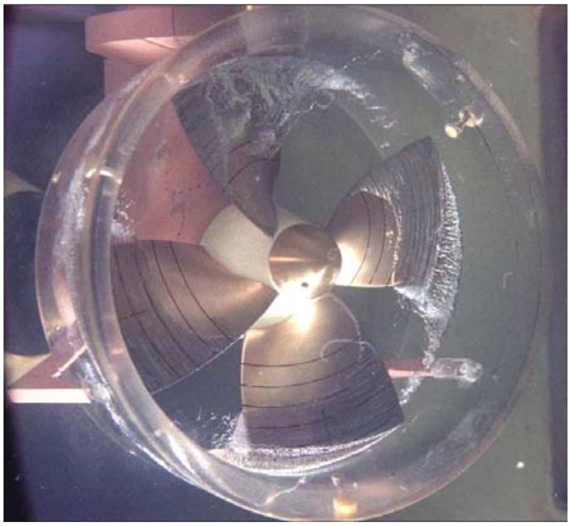

Figure 8 Thruster with Ka 4-70 propeller at T = 16.8 tons (K_T = 0.463)

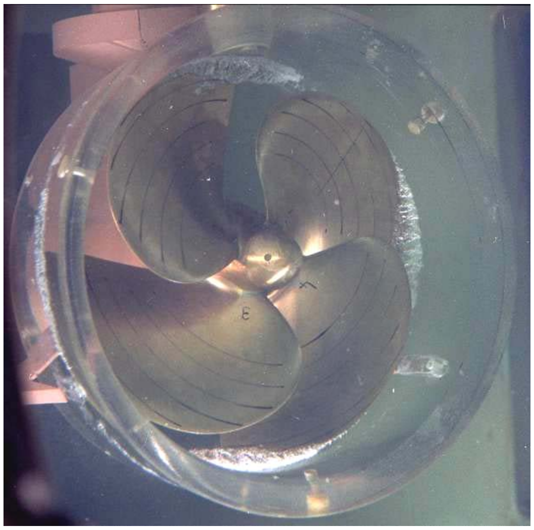

Figure 9 Thruster with design propeller at T = 14.8 tons (K_T = 0.408)

Strongly developed suction side sheet cavitation and tip clearance cavitation is now observed on the Ka propeller. The surface of the cavity on the upper blade is strongly disturbed by the presence of a PHV. The design propeller shows however still no leading edge sheet cavitation, but the tip clearance cavitation is more developed and bubble cavitation can be discerned near the trailing edge.
The cavitation in the tip region has about the same extent for both propellers. The fact that in this condition both propellers have about the same cavitation induced thrust decrease, indicates that the amount of sheet cavitation on the blade does not affect the thrust. The parameter that does influence the thrust of the propeller is the percentage of the blade that is supercavitating (cavitation extent > 100% chord length). Apparently sheet cavitation can be effectively reduced to zero by a combination of a larger blade area and optimised blade sections. The tip clearance cavitation that causes the thrust decrease is more difficult to predict with the used calculation method. A reduction of the tip pitch and camber are recommended to reduce this type of cavitation (see also Figure 11).
Cavitation on the main strut is shown by Figures 10 and 11 for the thruster with the Ka and the design propeller respectively. The extent of the sheet cavitation varied with the blade passage between almost zero and the extension as shown. The difference in cavitation extent between the two configurations is caused by the larger rotation induced by the Ka propeller because of its larger virtual pitch.

Erosion

Because of the pulling configuration, the sheet and tip clearance cavitation on the propeller are almost stationary. Therefore no erosion is expected on the propeller and nozzle from these types of cavitation. The bubble cavitation in the tip region of the design propeller and the sheet cavitation on the main strut are thought to be erosive. Although the operation times under severe conditions are relatively short, it is recommended to provide measures for this. A wear plate on the strut will prevent damage to the constrution of the thruster. The bubble cavitation can be removed by reduction of the camber in the tip area.

Figure 10 Thruster with Ka 4-70 propeller at V_{tip} = 47 m/s, T = 18.3 tons

Figure 11 Thruster with design propeller at V_{tip} = 46 m/s, T = 17.5 tons

Noise and vibration

The propeller induced pressure fluctuations were not measured during the model tests, but on basis of the cavitation observations some general remarks can be made on this subject:

- The imploding cavitation downstream of the propeller blades will cause a significant amount of noise which has to be taken into account in the positioning of the thruster on a ship.
- A pulling configuration with high rotation rates has only small variations of cavity volumes over the height of the propeller disk. Therefore the pressure fluctuations for a pulling configuration are estimated to be quite limited which in turn will cause only a small risk of vibrations.
- It is expected that a pushing configuration experiences larger variations in cavity volumes due to a larger wake peak and therefore has a higher risk of vibrations.
- If not prevented by metal strips on the hull or the natural varying azimuth angles and orbital water motions due to waves, PHV cavitation may cause strong vibrations on the hull and thruster system.

The present observations have been made at zero azimuth angle relative to the flow because of the limited dimensions of the test section. An oblique inflow angle, which is quite common in DP conditions, will cause variations in the cavity volumes on the blades and will therefore increase the risk of vibrations. However, a high rotation rate will make a propeller less susceptible to inflow variations.

Measurements

The effect of cavitation on the thrust curves of the Ka and design propeller is shown in Figure 12 by the solid lines. The calculated non cavitating curves are shown for reference purposes by the dashed lines. Likewise, the effect of cavitation on the torque curves of both propellers is shown in Figure 13. Several things can be noted when comparing the characteristics of the two propellers. Due to the higher effective pitch of the Ka propeller, both its thrust and torque curves are positioned higher than those of the design propeller. The thrust of the Ka propeller is influenced later (on basis of tip speed) by cavitation, but the point of 10% thrust influence is reached sooner. At 20 tons thrust, the system is close to thrust breakdown (horizontal tangent) which corresponds with the propeller blades fully covered with cavitation. The design propeller performs better; the thrust curve is almost a straight line and does not show any sign of thrust breakdown.

The torque curves of both propellers show similar trends as their thrust curves. Clearly, cavitation decreases the torque of the propellers, but at a smaller rate than the thrust. This has a decreasing effect on the efficiency.

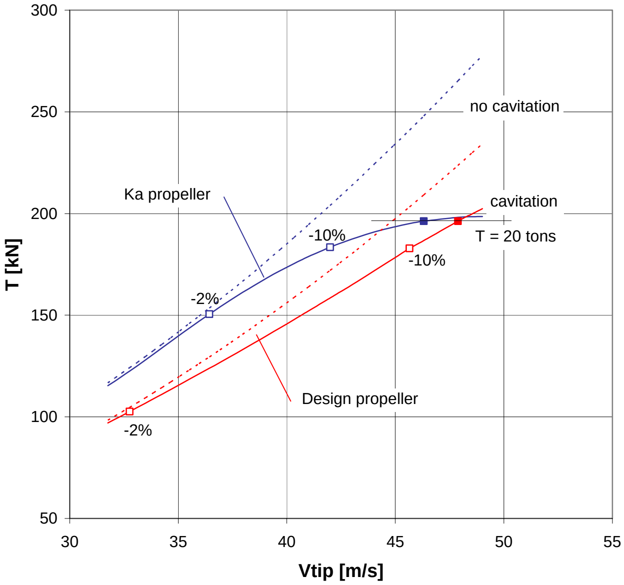

Figure 12 Effect of cavitation on thrust in bollard pull condition, D = 1.41 m

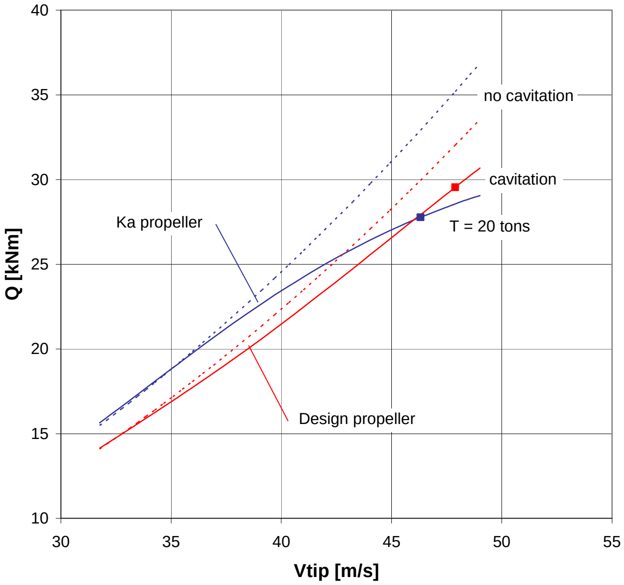

Figure 13 Effect of cavitation on torque in bollard pull condition, D = 1.41 m

The measured thrust data is shown in the non dimensional design space in Figure 14 as a blue and green curve. The Ka 4-70 propeller has a relatively high thrust density at the point of thrust influence. This is the effect of the blade area ratio, because all other points (except for the design propeller) are formed by propellers with smaller blade area ratios. Further, this diagram shows that the envisaged thrust density ($K_T/\sigma_n = 0.377$) is realized close to the design point.

The table below shows a comparison between characteristics of a reference thruster at a common tip speed, the design objective and the tested thruster with stock (Ka) and design propeller. All thrusters deliver a thrust of 20 tons at the bollard pull condition. This comparison shows that a reduction of the propeller diameter with 27% can only be realized at a significant increase in the propeller shaft power of 60 to 80%.

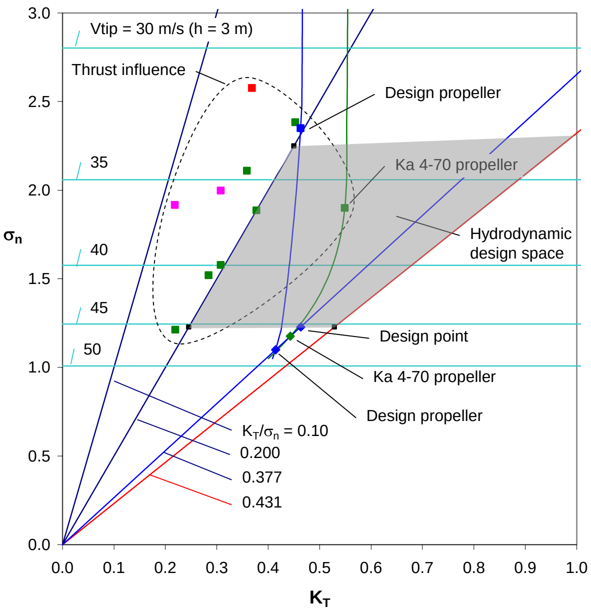

Figure 14 Test results projected in original design space

Thruster	D [m]	P [kW]	Vtip [m/s]	T/P [kg/hp]	η_E [-]	K_T/σ_n [-]
Reference	1.94	1119	33.5	13.1	1.00	0.20
Design objective	1.41	1635	45.3	9.0	0.94	0.38
Model tested with Ka propeller	1.41	1825	46.3	8.1	0.84	0.38
Model tested with design propeller	1.41	2009	47.9	7.3	0.76	0.38
Medium thrust density with Ka propeller	1.52	1471	39.3	10.0	0.97	0.33

Almost half of this increase is due to the increase of the loading. The further increase is caused by the effects of cavitation on thrust and torque of the propeller, the unfavourable interaction between the nozzle and the thruster gondola and in the case of the design propeller: the increased blade area. As a result of the increased power, the gondola/propeller diameter ratio increases. Applying the reduction found in the current specific design relative to the general relation as shown in Figure 4, this ratio becomes 0.44 for the thruster with the design propeller.

In order to explore the design space somewhat further, a compromise was sought between decrease in propeller diameter and increase in power. Based on the cavitation test data with the Ka propeller and aiming at a bollard pull efficiency of 10 kg/hp, a thruster with medium thrust density was found. The values in the table above show that with an increase of the power with 31%, the propeller diameter can be reduced with 22%.

Thruster size and cost

Based on the data presented above, preliminary drawings of a conventional thruster, a medium density and a high density thruster are presented in Figure 15. All thrusters are configured as retractable units. The decrease of the propeller diameter gives a significant gain outside the hull. Inside the hull some height is gained, but some space is lost again due to the larger cooling unit of the electric motor. The medium density thruster shows a good compromise and gains space inside and outside the hull.

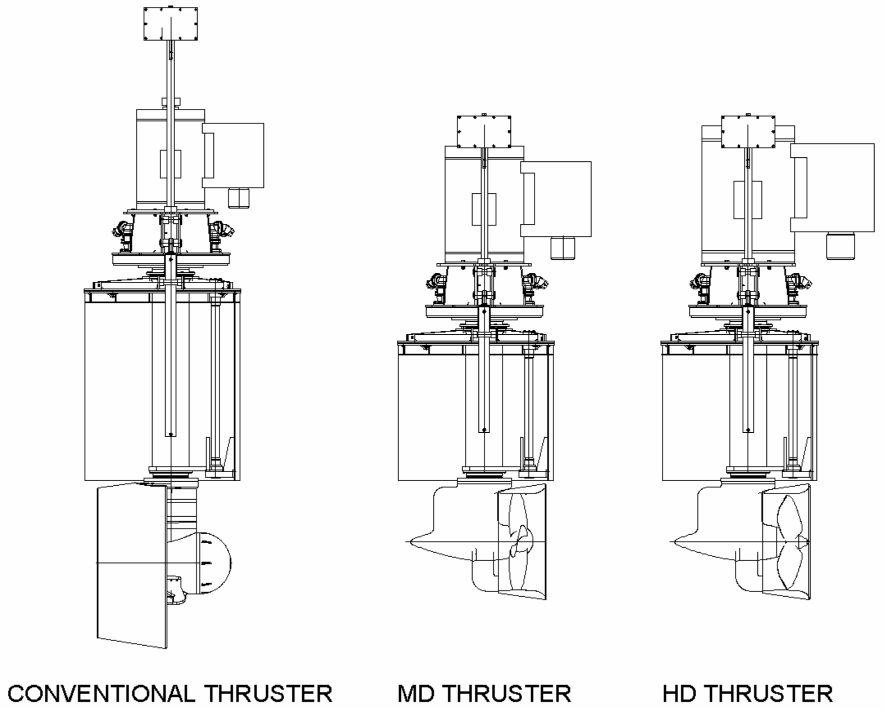

Figure 15 Comparison of thruster size for T = 20 tons

A comparison of the acquisition cost shows that the cost of the mechanical part of the thruster is reduced some, but due to the large increase of the cost of the electric motor, the total acquisition cost increase. For the high density thruster the acquisition cost increase with 25%, but for the medium density thruster the cost increase with only 8%.

The operational cost increase with estimated values of about 50% and 15% for the high density and medium density thruster respectively. These values are lower than the increase in installed power because it is assumed that DP thrusters do not operate continuously at full power.

Concluding remarks

- Using a pulling propeller concept, a significant reduction in propeller diameter can be achieved relative to a conventional thruster design at a thrust of 20 tons. The power input has increased significantly also.
- The higher required power creates a limit in the minimization of the overall dimensions because of the size of the electric drive system.
- A moderate reduction of the propeller diameter is therefore advised, which makes a compromise between gain in dimensions and additional cost.
- The Ka propeller was found to be close to cavitation induced thrust breakdown at the envisaged thrust density. The design propeller showed no signs of thrust breakdown up to the maximum tested tip speed. This improved cavitation behaviour was however reached at the cost of an decrease in efficiency.
- A propeller designer may therefore accept limited sheet cavitation as a compromise between delay of cavitation induced thrust influence and efficiency.
- Future model tests on high thrust density thrusters should preferably be conducted in MARIN's depressurized towing tank where a better representation of the full scale condition can be obtained by testing the bollard pull condition and oblique inflow angles without wall effects. In order to determine the risk of vibrations on a more quantitative basis, additional propeller induced pressure pulse measurements are recommended.

Nomenclature

A_0	propulsor disc area	$[m^2]$
A_e	expanded blade area	$[m^2]$
D	diameter	[m]
g	acceleration of gravity	$[m/s^2]$
h	shaft submersion	[m]
J	advance coefficient $=V/(nD)$	[-]
K_Q	torque coefficient $= Q/(\rho n^2 D^5)$	[-]
K_T	thrust coefficient $= T/(\rho n^2 D^4)$	[-]
n	propulsor rotation rate	$[s^{-1}]$
P	propeller pitch	[m]
P_d	delivered power	[W]
P_0	atmospheric pressure	[Pa]
P_v	vapour pressure	[Pa]
Q	propeller torque	[Nm]
r	radius	[m]
T	propulsor thrust	[N]
U, V	velocity	[m/s]
V_{tip}	propeller tip speed $= \pi nD$	[m/s]
Z	number of blades	[-]
η_O	open water efficiency $= JK_T/(2\pi K_Q)$	[-]
η_E	merit coefficient $= (K_T/\pi)^{1.5}/(\sqrt{2}K_Q)$	[-]
ρ	density of water	$[kg/m^3]$
σ_n	propeller cavitation number $= (P_0-P_v+\rho gh)/(½\rho n^2 D^2)$	[-]

Acknowledgements

The authors wish to thank those people and companies that have contributed to the work presented here. The work was co-sponsored by a Joint Industry Project, the Dutch Ministry of Economic Affairs and MARIN. Participants to this Joint Industry Project are: Breeman Engineering and Services, Damen Shipyards, Holland Roer Propeller, IHC Caland, Smit Engineering and Van Ommeren Shipping.

References

[1] Van Rijsbergen, M.X., and Van Terwisga, T.J.C., 2000, "On the Maximum Thrust Density of Propellers", NCT '50 International Conference on Propeller Cavitation, Newcastle

[2] Prishchemikhin, Y.N., 1975, "A Study of the Cavitating Propeller and Ship Hull Interaction in Cavitation Towing Tank", 14th ITTC Report of the Propeller Committee Appendix 3, Ottawa