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Aspects of the Design Procedure for Propellers Providing Maximum Bollard Pull

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SYNOPSIS

The number of tugboats worldwide, their size and their power are all increasing rapidly. Their most important design and operation criterion is the available bollard pull. The propeller manufacturers are trying to increase the delivered power and the system diameter of the ducted propellers to meet all requirements. This has led to a higher power density of the ducted propeller and to a greater risk of cavitation. That is why the design process is complex and has to rely on calculations and model tests. An important aspect regarding the bollard pull of highly loaded ducted propellers is the cavitation behaviour; this is the reason that the results of model tests are increasingly necessary in the design process for tugs and their propellers. In conjunction with the model tests and the resulting thrust prognosis, the influence of Reynolds number effects has to be considered in the full-scale correction of the model thrust. This paper will present the major results of the investigations regarding cavitation of ducted CP propellers at bollard pull condition and will show the main aspects that can influence the bollard pull. Based on an example of a 220 tonne tug with ducted conventional CP propellers, it will be shown that both the shape of the aft ship and the propeller design have to be optimised in order to realise the maximum possible bollard pull.

1. INTRODUCTION

Schottel Rudderpropellers have been serving tugs for more than 40 years. Schottel is continuously working to improve each component of the Rudderpropeller: the nozzle, the propeller, the housing and the mechanical parts. In recent years the required bollard pull has been increasing very quickly along with the growing sizes of built vessels worldwide which have to be handled by tugs. The company is now talking about an input power for one ducted standard Rudderpropeller of about 5,000kW and propeller diameters of about 4.6m. The thrust of one unit exceeds 100 tonnes. For Schottel's conventional ducted CP propellers the input power has reached the 8,000kW mark, whereas the unit thrust has passed 135 tonnes.

The development of the dimensions of the tugboats themselves has been restricted mainly by the required high manoeuvrability. In addition, the propeller should still not extend below the base line of the tug. There is only limited space in the stern for installation of the thrusters. This results in the concentration of more and more power on the tugboats in order to achieve a maximum bollard pull. For fixed-pitch ducted Rudderpropellers, the blade load reaches values of 500kW/m^2 and more.

With this progressive development, the design of the propellers and nozzles is approaching hard hydrodynamic limits, especially due to cavitation. Therefore, the focus of our work is to keep the propeller and the nozzle still working at maximum power with a minimum loss of thrust caused by cavitation. In the past 10 years, Schottel has gained a lot of experience with ducted Rudderpropellers working in critical hydrodynamic conditions.

Nowadays, the company has to put more effort into the design of ducted propellers, providing higher maximum bollard pull than ever before. The arrangement of the stern part of the tug, the installation situation of the thruster in general and the operation conditions in service have to be investigated in order to ensure the required pulling performance.

For further improvements and the reliable prognosis of the bollard pull, it is increasingly necessary to raise the budget for investigations and to make use of model test basins. Schottel has already invested a lot of time and manpower to improve the understanding of the factors which influence the performance of ducted propellers during bollard pull. In the following chapters, some examples of the investigations carried out with SVA Potsdam are described.

2. JOINT RESEARCH AND DEVELOPMENT IN THE FIELD OF DUCTED PROPELLERS FOR TUGS

Continuous research and development work is necessary for the improvement of the products and the design procedures. Schottel and SVA Potsdam have carried out various joint R&D projects in the field of thrusters and ducted propellers in the past few years.

2.1 Thrusters

The thrusters of type SRP 1212, SRP 1515 and SRP 2020 were investigated in model tests and calculations[1]. In particular, the geometry of the thruster housing and the arrangement of the ducted propeller at the thruster housing were optimised by Schottel. SVA Potsdam developed new measuring devices (balances and Z-drive dynamometers) for thruster tests, and investigated different ducted propeller designs by potential and viscous flow calculation methods.

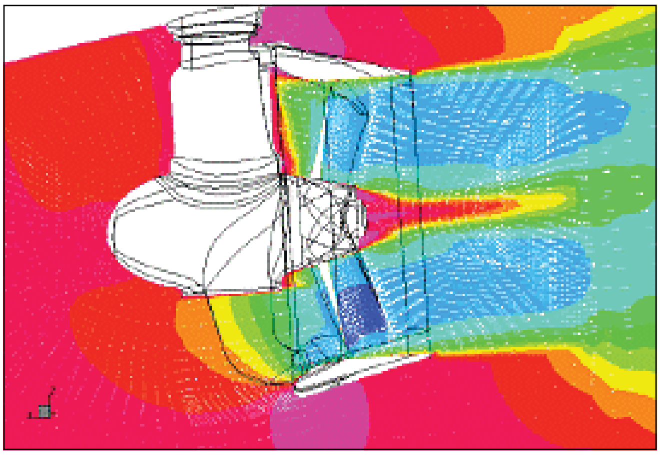


Figure 1: Axial velocity components in a longitudinal section of an SRP.

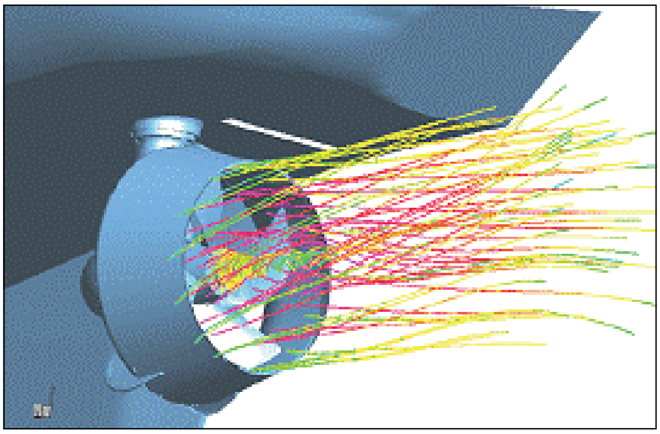


Figure 2: Stream lines in the propeller jet.

2.2 Reynolds Number Effect

The aim of an extensive R&D project at SVA Potsdam concerning thrusters with ducted propellers was the investigation of the viscous flow with different Reynolds numbers and loading conditions, to get a better understanding of the behaviour of ducted propellers and to improve the accuracy of the extrapolation methods. Schottel supported the R&D work with full-scale measurements.

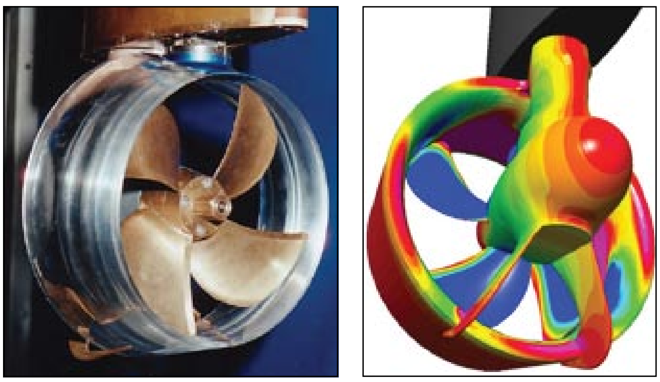


Figure 3: SRP in model test and CFD calculation (pressure distribution).

The numerical full-scale results show that the flow velocity in the nozzle is comparatively higher than in model scale. This fact leads to an increase of the nozzle thrust and to a reduction of the thrust and of the torque of the propeller. The influence of the Reynolds number on the torque of a ducted propeller is consequently higher than on a free-running propeller[2]. That may be an explanation for the often observed too lightly loaded propellers in full-scale which were designed on the basis of test results in model scale.

Figure 4 shows the change of the ducted propeller coefficients for Reynolds number ratios $1 \leq R_{nS}/R_{nM} \leq 100$, calculated for a propeller of type KA 5-75 in a nozzle 19A.

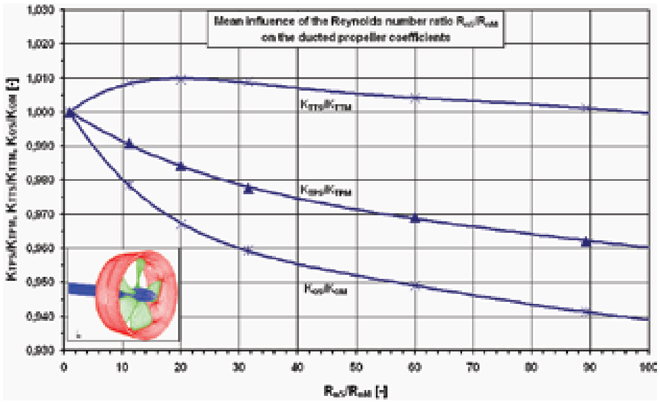


Figure 4: Influence of the Reynolds number ratio on the change of the ducted propeller coefficients.

An estimation method for the Reynolds number effects of ducted propellers was developed on the basis of CFD calculations for four ducted propellers and model and full-scale measurements[3].

2.3 Thrust Breakdown Due To Cavitation

Cavitation tests have been part of the development of thrusters and ducted propellers for the past 15 years. The model tests showed that the cavitation behaviour must be taken into consideration in the design and optimisation process especially for ducted propellers with high thrust loading coefficients. To study the influence of cavitation on the thrust of a ducted propeller at bollard pull condition, an R&D project was initiated. Systematic tests with ducted propellers showed that the thrust breakdown of ducted propellers is caused mainly by the reduction of the nozzle thrust. *Figures 5* to *7* show the influence of the blade outline on the ducted propeller coefficients during variation of the cavitation number at high thrust loading (low advance coefficient). The propeller model VP 1303 represents a propeller with a Kaplan blade type. The model propeller VP 1305A is a propeller with a diminishing chord length at the blade tip. Both propellers were tested in the nozzle D 221, type Wageningen 19A.

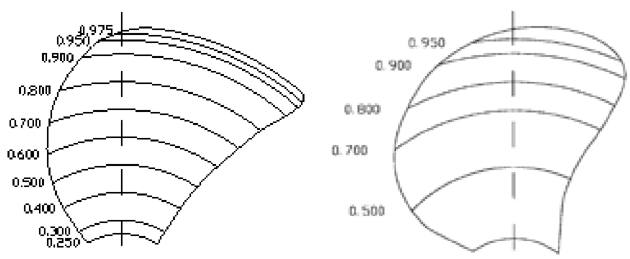


Figure 5a: Blade outlines – left, Kaplan blade shape VP 1303; right, diminishing chord length at the blade tip VP 1305A.

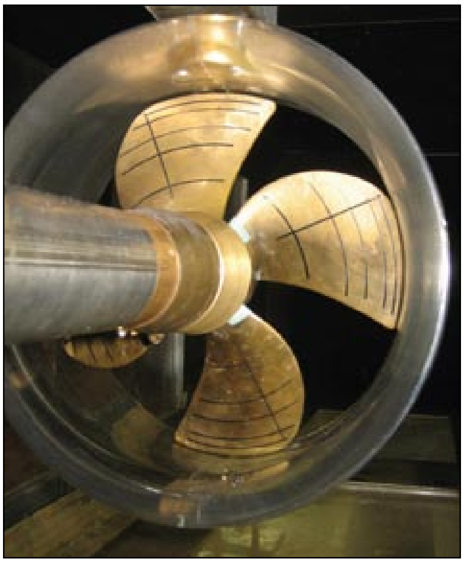


Figure 5b: Test arrangement with VP 1303.

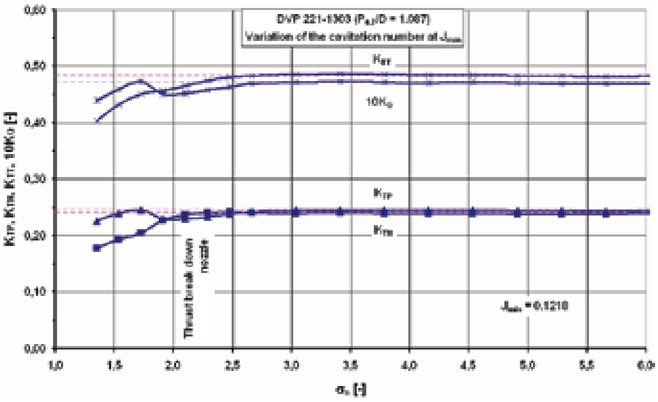


Figure 6: Variation of the cavitation number, DVP 221-1303.

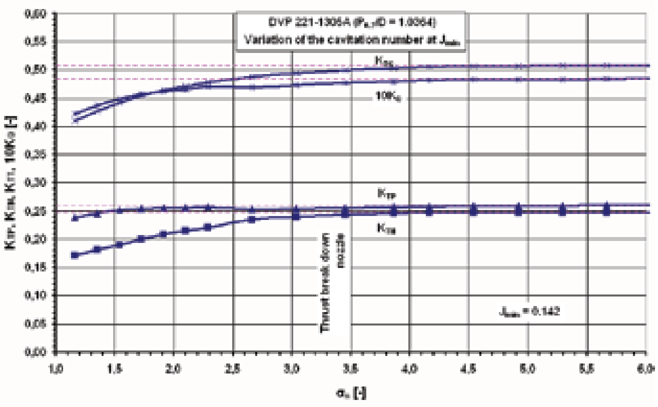


Figure 7: Variation of the cavitation number, DVP 221-1305A.

The investigations show that the chord length at the blade tip is very important for influencing the cavitation behaviour and thereby the thrust breakdown. The analysis of the cavitation gives the indication that the thrust breakdown of the nozzle starts if cavitation appears over the whole revolution at the blade tip profile.

The video prints with the cavitating propellers at the cavitation number for the inception of nozzle thrust breakdown show a smaller degree of cavitation on the propeller VP 1305A (*Figure 8*). Nevertheless, the thrust breakdown starts distinctly earlier on the ducted propeller with a blade outline with diminishing chord length at the blade tip.

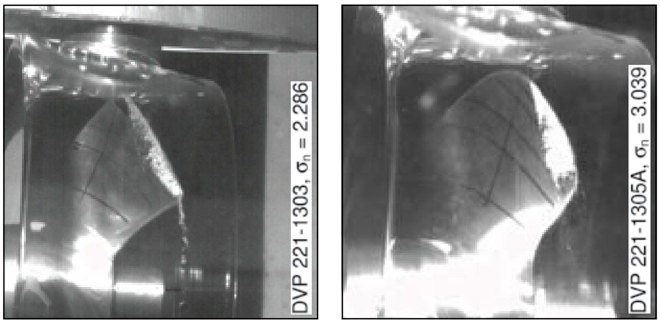


Figure 8: Cavitation behaviour at the cavitation number for the inception of nozzle thrust breakdown.

Extensive CFD calculations have been carried out to find the reason for nozzle thrust breakdown due to the relatively low cavitation. First, the calculations have shown that it is possible to predict the cavitation behaviour and the thrust breakdown due to cavitation. Also, the CFD calculations provide an opportunity to study flow details, as shown in *Figure 9*.

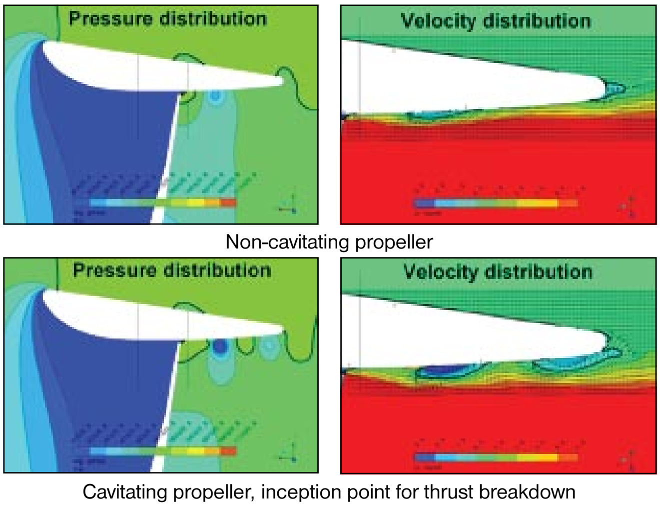


Figure 9: Pressure and velocity distributions at different cavitation numbers, C_{TH} = 70.

The cavitating tip vortex disturbs the flow in the diffuser of the nozzle. The result is flow separation and backwards flow. The thrust breakdown of the nozzle is connected with the flow in the diffuser area. It can be shown that the nozzle thrust decreases if the outflow area is reduced by flow separation. The flow separation in the diffuser also has the effect of increasing the propeller thrust and torque.The results of the cavitation tests with different ducted propellers are summarised in *Figure 10*. This diagram made it possible to predict the risk of thrust breakdown in the early design stage.

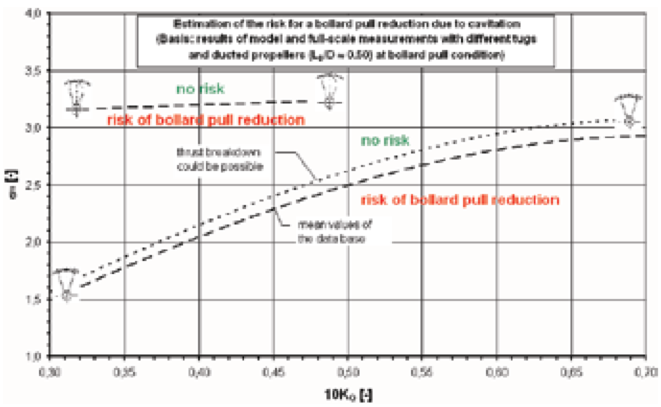
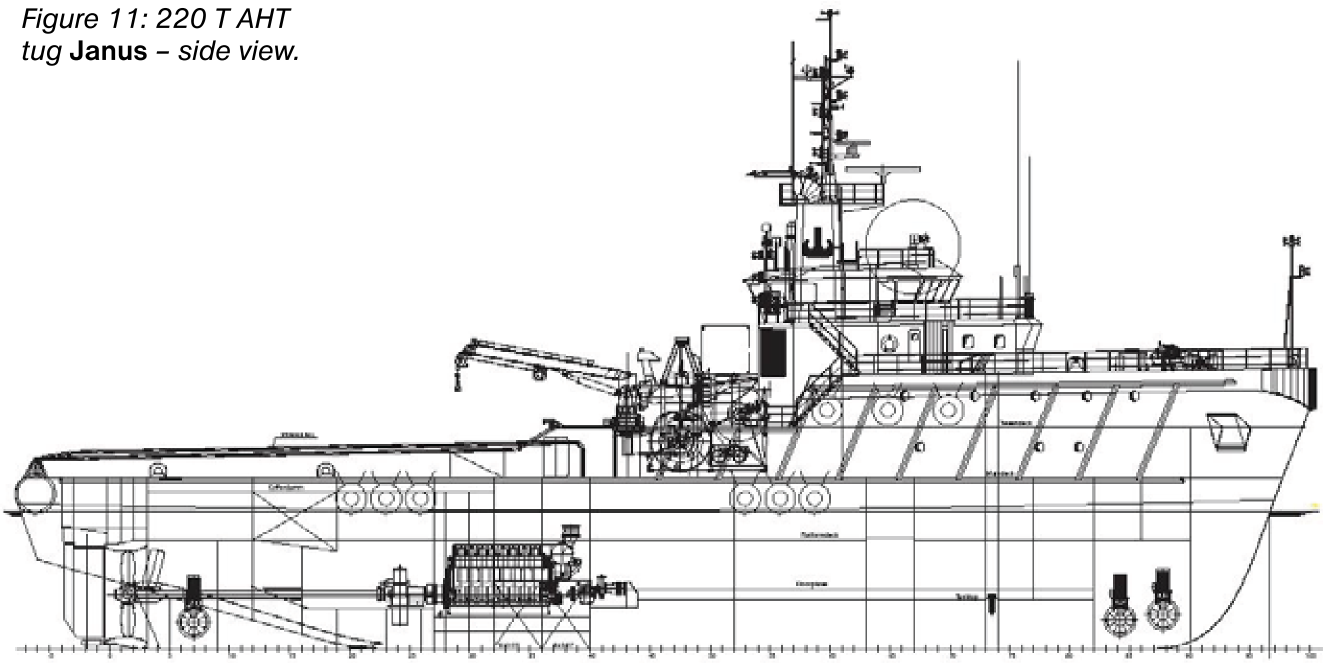


Figure 10: Estimation of the risk of bollard pull reduction due to cavitation.

Figure 11: 220 T AHT tug **Janus** *– side view.*



3. *JANUS* AND *URSUS* – AHT WITH 220 TONNES BOLLARD PULL

In November 2005, together with MAN Ferrostaal AG, Schottel-Schiffsmaschinen GmbH in Wismar signed a contract to supply the controllable-pitch propellers for the most powerful German ocean-going tugs ever built, with a bollard pull of 220 tonnes (*Figure 11*). The vessels are being built by Mützelfeldtwerft in Cuxhaven for Harms Bergung Transport & Heavylift GmbH & Co. KG in Hamburg.

The main data for the tugs is summarised in *Table 1*.

Length over all	L_{OA}	[m]:	65.00
Breadth	B	[m]:	18.50
Draught	T	[m]:	6.80

Table 1: Main dimensions of the tug.

The propulsion units are powered by four MaK engines, rated at 3,000 and 4,000kW per shaft. Schottel-Schiffsmaschinen GmbH supplied SCP 119/4XG-type controllable-pitch propellers. The vessels are additionally to be fitted with three Schottel Transverse Thrusters of type STT 330 T-LK (400 kW each). The propeller design parameters in the early design stage are presented in *Table 2*.

Diameter	D	[m]:	4.40
Delivered power	P_D	[kW]:	2 x 6790
Number of revolutions	n	[rpm]:	140

Table 2: Design data for the ducted propeller.

In the following chapters, aspects of the design process of the CP propellers for the AHT will be discussed.

3.1 Influencing Factors for the Bollard Pull

The propulsion system, the ship hull and the arrangement of the propulsion system on the ship are the main influencing factors for the available bollard pull.

A well-known way to analyse the efficiency of propulsion systems in bollard pull condition is to use the so-called 'pump efficiency' (*Formula 1*), (or 'figure of merit' or 'Quality Index').

Formula 1: Pump efficiency.

$$\eta_{PP} = \frac{D_P}{D_0} * \sqrt{\frac{K_{TT}^3}{2*\pi^3*K_Q^2}} = \frac{\sqrt{\frac{2*T^3}{\rho*\pi}}}{P_D*D_0} = \frac{\eta_0}{\eta_i}$$

with D_P - propeller diameter, D_O - outer nozzle (propulsion system) diameter, K_{TT} – total thrust coefficient, K_Q - torque coefficient (both determined with respect to D_P), η_i - ideal efficiency and η_0 - open water efficiency.

There is a limit for J ➔ 0 of $\eta_0(J)/\eta_i(J)$, which is equal to the bollard pull efficiency. It can be deduced following the momentum theory that the total thrust of the propulsion system can be directly computed from the following equation with respect to the formula for η_{PP}.

Formula 2: Bollard thrust.

$$T_T = \sqrt[3]{\frac{\pi\cdot\rho\cdot(D_0\cdot\eta_{PP}\cdot P_D)^2}{2}}$$

The equation for the bollard pull (*Formula 2*) shows that the bollard thrust can be raised by increasing the outer diameter, the delivered power and the pump efficiency.

The propeller hull interaction has to be taken into account in the design process. The working propeller generates a pressure reduction on the hull in the condition bollard pull ahead. The difference between the bollard thrust of the propeller T_T and the bollard pull of the tug F_D can be represented by the thrust deduction factor t (*Formula 3*).

Formula 3: Thrust deduction factor.

$$t = (T_T - F_D) / T_T$$

The buttock slope and the hull-nozzle clearance are the main geometric parameters for the thrust deduction factor. A reduction of the slope and an increase of the clearance will decrease the thrust deduction factor[5,6].

To achieve a large diameter of the propulsion system and an optimum fixing of the nozzle, the nozzle is often partly integrated in the ship hull or in a head box. Partial integration of the nozzle in the range of 90 degrees has a relatively low influence on the ducted propeller coefficients. The total thrust is similar to the ducted propeller without integration. Distribution between the propeller and nozzle thrust changes due to the partial integration of the nozzle.

3.2 Ducted Propeller Design

A new nozzle profile was used by Schottel for the ducted propeller. The nozzle is a part of the propulsion system which can produce more thrust than the propeller at bollard pull condition. The inflow of the propeller is directly affected by the geometry of the nozzle and vice versa.

The relevant parameters for the nozzle design are the length ratio of the nozzle, the entrance cross-section ratio, the exit cross-section ratio and the nozzle profile. Aspects of flow separation, demands for special characteristics (reverse drive) and technological requirements reduce the variation of the nozzle profile. The influence of the nozzle profile variation on the ducted propeller characteristics cannot just be investigated in open water tests!

Results of systematic model tests with ducted propellers show that at high thrust loading coefficients, the length ratio of the nozzle should be $L/D_I = 0.7$[7]. The entrance cross-section ratio should be in the range of 1.3 to 1.35 and the exit cross-section ratio in the range of 1.1 to 1.13.

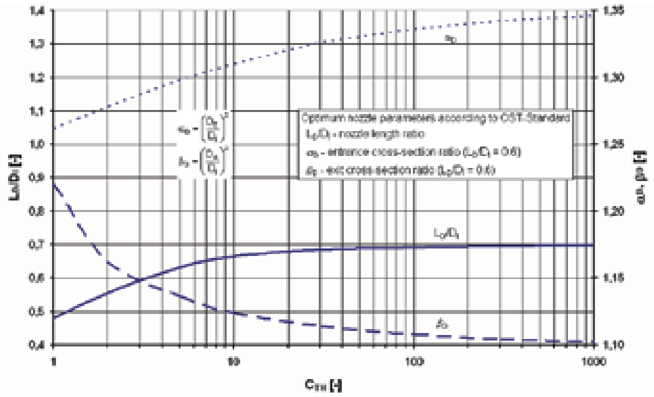


Figure 12: Optimum nozzle parameters (OST Standard[8]).

Nozzle variant		No. 1	No. 2
Length ratio	L/D_I [-]:	0.500	0.500
Entrance cross-section ratio	A_E/A_I [-]:	1.320	1.286
Exit cross-section ratio	A_A/A_I [-]:	1.165	1.134
Position of propeller	x_P/L [-]:	0.500	0.500

Table 3: Data of nozzle variants for the ducted propeller.

The controllable-pitch propeller was designed by Schottel in cooperation with SVA Potsdam. With the propeller diameter of $D_P = 4.40$m the following design (*) parameters were given.

Advance coefficient	J^*	[-]:	0.000
Torque coefficient	K_Q^*	[-]:	0.0503
Total thrust coefficient	K_{TT}^*	[-]:	0.515
Cavitation number	σn^*	[-]:	2.616

The comparison of these design parameters with the database regarding the risk of thrust breakdown (*Figure 10*) showed a danger of exactly that problem due to cavitation. That is why the main aim of the propeller design was optimum cavitation behaviour at bollard pull condition.

The propeller was designed like a free propeller subject to inflow influenced by the duct for the available power and actual speed. The hydrodynamic model for the calculation of the inflow in the propeller plane of the ducted propeller is a lifting line method with corrections for the effect of the lifting surface[8]. A lifting surface method was used for propeller optimisation. The design process was carried out iteratively in several loops. In particular, the blade outline and the pitch and chamber distribution were varied.

The first model tests were carried out with the propellers VP 1466 and VP 1467. After the tests the nozzle profile was changed by a small degree and the propeller diameter was increased from 4.4 m to 4.5 m. The calculations and tests showed excessively high torque (power) at the zero thrust condition of the tug. The ducted propeller was optimised again to reduce the power at this condition. The area ratio and the chamber of the propeller blades had to be reduced in this design step. The model propellers VP 1499 and VP 1500 are similar to the final propellers on AHTs ***Janus*** and ***Ursus***.

Model propellers:				VP 1466 VP 1467	VP 1498	VP 1499 VP 1500
Diameter	D_S	[m]	:	4.40	4.50	4.50
Diameter	D_M	[m]	:	0.22	0.225	0.225
Pitch ratio	$P_{0.7}/D$	[-]	:	1.009	1.015	1.015
Area ratio	A_E/A_0	[-]	:	0.704	0.701	0.624
Skew angle	θ_{EXT}	[°]	:	24.65	24.935	24.357
Hub diameter ratio	d_h/D	[-]	:	0.256	0.250	0.250
Number of blades	Z	[-]	:	4	4	4

Table 4: Data of various designed propellers.

The designed propellers are characterised by a blade outline with a long chord length at the blade tip (see *Figure 13*).

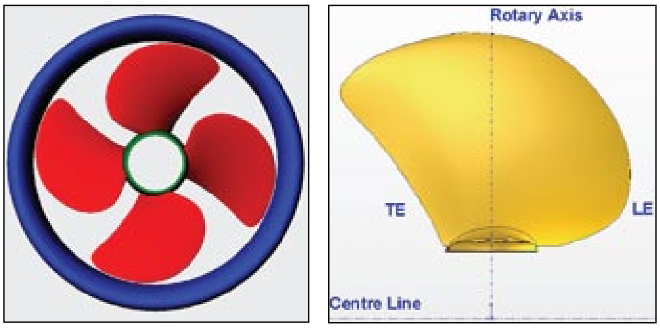


Figure 13: Propeller VP 1466 in nozzle and 3D model of full-scale propeller (Dp = 4.40m).

3.3 Model Tests

3.3.1 Bollard Pull Measurements

SVA Potsdam was commissioned by MAN Ferrostaal AG to carry out resistance and propulsion tests and static bollard pull measurements with the model of the AHT (M1236Z000). For these tests the model was equipped with the designed ducted propellers from Schottel.

The bollard pull measurement was carried out for nine revolutions in the range from 70rpm to 160rpm. Test results have been extrapolated to full scale by R_n-number revaluation of the open water characteristic and a pitch correction.

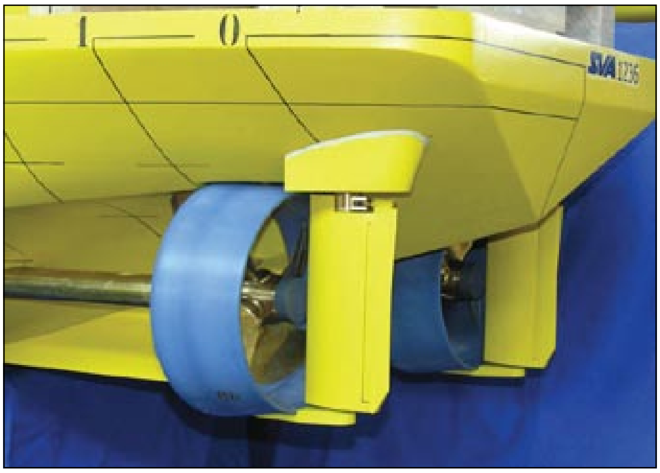


Figure 14: Aft ship of the model M1236Z010.

The bollard pull measurements showed a thrust deduction factor $1\text{-}F_D/T_T$ = 0.113. The bollard pull was calculated as F_D = 221.2 tonnes for P_D = 2 x 6790kW and n = 140 rev/min.

The analysis of the test results showed that the thrust deduction factor had to be reduced. That is why the aft ship lines were optimised. The buttock slope angle was reduced ($\Delta\varphi$ = -3°) and the vertical hull-nozzle clearance was increased. The bollard pull measurements with the modified model of the AHT (M1236Z010) delivered a thrust deduction factor $1\text{-}F_D/T_T$ = 0.080. *Table 5* shows a comparison of the predicted pitch ratios, bollard pulls and thrust deduction factors for both tug variants. Minimising the thrust deduction factor results in a better inflow to the ducted propeller. The result is a higher pitch ratio of the propeller and a smaller interaction between the ducted propeller and the aft ship.

Model	P/D	F_D	$1\text{-}F_D/T_T$
	[-]	[t]	[-]
M1236Z000	1.0043	221.2	0.113
M1236Z010	1.0101	225.6	0.080

Table 5: Bollard pull prognosis and thrust deduction factors, models M1236Z000 and M1236Z010.

3.3.2 Cavitation Tests

The data base regarding the thrust breakdown due to cavitation showed a risk for the ducted propeller system on the 220t tug, as discussed in chapter *3.2*. That is why cavitation tests with the free-running ducted propeller were carried out in the cavitation tunnel of SVA Potsdam. The cavitation number was varied at high thrust load coefficients to observe the cavitation inception, to study the cavitation behaviour and to obtain information about the forces and moments.

With homogeneous inflow, tip vortex cavitation occurs at the propeller only. Nevertheless, inception of nozzle thrust reduction could be seen at cavitation numbers smaller than 2.9 (*Figure 15*). That means a risk of thrust breakdown for the full-scale propeller.

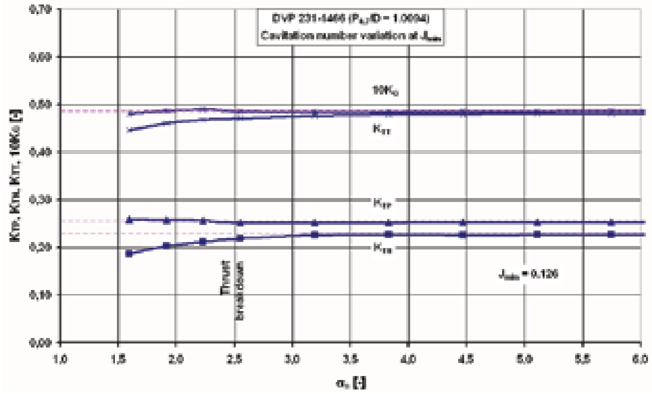


Figure 15: Variation of the cavitation number, DVP 231-1466, first propeller design.

The influence of cavitation on the forces and moments of the ducted propellers and the thrust deduction factor is not included in the bollard pull prognosis on the basis of tests in the towing tank. Schottel and SVA decided to carry out additional cavitation tests with the model of the AHT (M1236Z010) in the large circulating and cavitation tunnel UT2 at Berlin Technical University. The test section of this tunnel with a length of 11.0m, a width of 5.0m and a depth of 3.0m allows tests at bollard pull conditions. *Figure 16a* shows the model during installation in the UT2. Measurements in the UT2 were carried out at a water velocity V_S = 0 and different numbers of revolutions at atmospheric pressure and at pressures corresponding to the model and full-size cavitation numbers.

Figure 16a: Model M1236Z010 in the test section of the UT2.

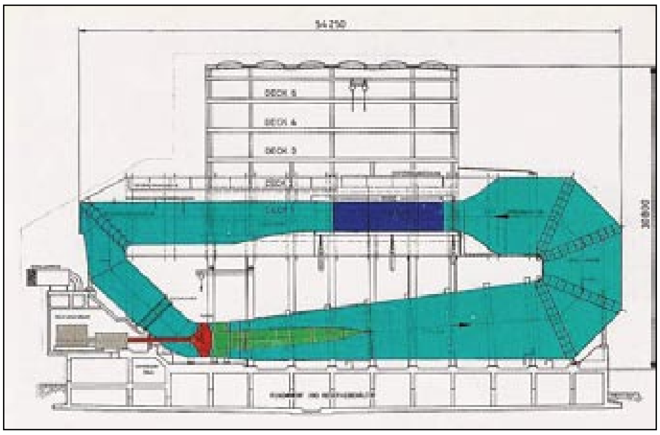


Figure 16b: Side view of the UT2.

In the range of the design power there is an inception point for bollard pull loss due to cavitation (*Figure 17*). Analysis of the propeller and nozzle thrust measurements shows that the cavitation has only a small influence on the propeller thrust. The reason for bollard pull reduction is mainly the thrust breakdown of the nozzle. In addition there is an influence of cavitation on the thrust deduction factor (*Table 6*). The video prints in *Figure 18* give an impression of the cavitation behaviour. Tip vortex and suction side cavitation occurs on the propeller blade. The maximum cavitation extent occurs in the angle range where the nozzle is partly integrated in the hull. The thrust loading of the propeller is especially high in this region due to the bad inflow condition (risk of propeller hull vortex cavitation).

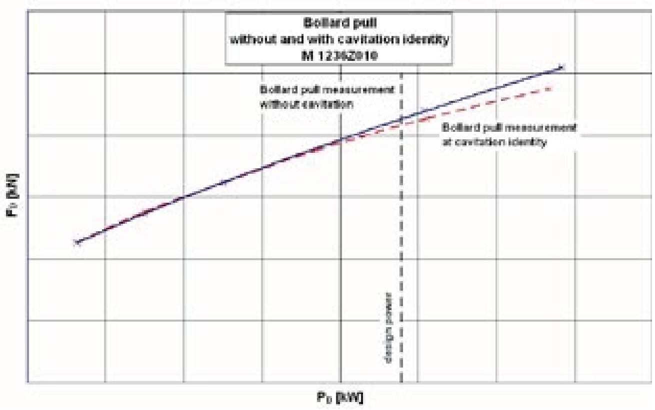
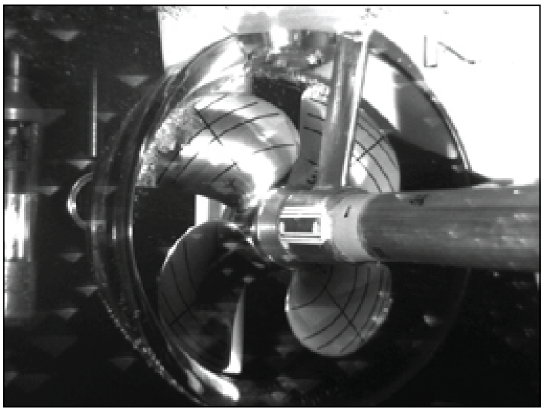


Figure 17: Bollard pull without and with cavitation identity, M1236Z010.

σ_n	K_{TPcav}/K_{TP}	K_{TNcav}/K_{TN}	K_{TTcav}/K_{TT}	K_{Qcav}/K_Q	K_{FDcav}/K_{FD}
5.10	1.021	1.009	1.006	0.997	1.004
4.22	1.016	1.003	1.003	0.998	1.009
3.54	1.014	1.004	1.001	0.999	0.997
3.02	1.007	0.988	0.989	0.996	0.990
2.60	1.003	0.964	0.976	0.990	0.963
2.27	0.999	0.923	0.955	0.980	0.932

Table 6: M1236Z010 – Influence of cavitation on the forces and moments.



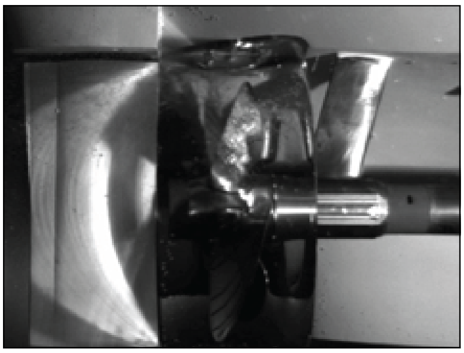


Figure 18: Cavitation observation model M1236Z010, σ_n = 2.60 (cavitation identity).

3.3.3 Bollard Pull Prognosis

An accurate estimation of the Reynolds number effect on the performance of ducted propellers is very important for extrapolation of the model results to full-scale[2,3]. Schottel and SVA Potsdam are using the Reynolds number correction for ducted propellers[3]. The Reynolds number correction for the model of the tug with the final propellers delivers an increase of the bollard pull by 4.8 per cent for the tests without cavitation, and 4.2 per cent for the tests at cavitation identity. The prognosis of the available bollard pull for the AHT is influenced by the cavitation (*Figure 19*).

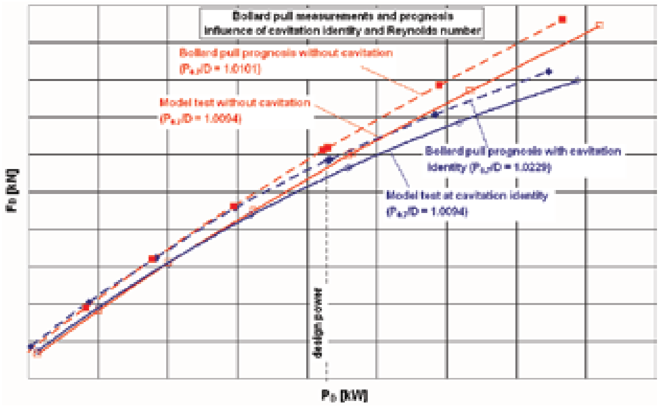


Figure 19: Bollard pull prognosis.

3.3.4 Trials

Bollard pull tests with AHT ***Janus*** were carried out in Stavanger, Norway in October 2007. The measurements by the engineering office Nolte & Szczesnowski showed a bollard pull of 219 tonnes.

Figure 20: 220 T AHT tug **Janus** *at sea trial.*

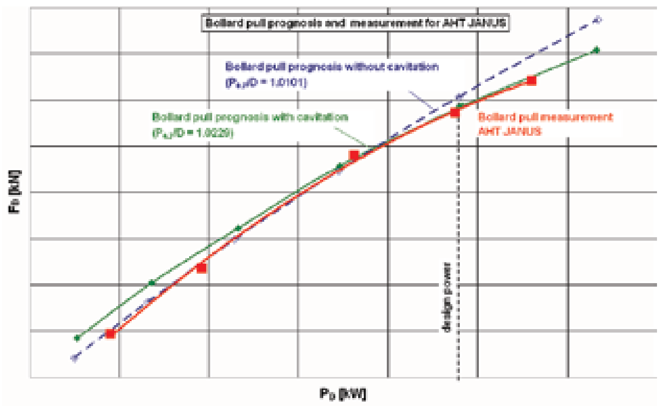


Figure 21: 220 T AHT tug **Janus***, comparison of bollard pull prognosis and measurement.*

Figure 21 presents the bollard pull prognosis and the model test results with and without cavitation compared with the full-scale measurements with AHT ***Janus***. The pitch ratio of the propeller was predicted for the MCR point. It can be seen that there is a good agreement between the prognosis based on tests with cavitation identity and the full-scale measurement. The prognosis based on tests without cavitation identity delivers excessively high bollard pull values.

4. CONCLUSIONS

The design of ducted propellers for tugs delivering maximum bollard pull requires much more than determining the propeller pitch for specified engine power and propeller rev/min. Our experience of recent years and especially the concentration on the propeller design for the 220T AHT tug has enabled us to gain more insight into the physics of the viscous flow inside a duct and the interaction between propeller and nozzle.

In addition to the hull lines at the stern part of the tug, which influence the thrust deduction factor, optimum geometry of the nozzle is required to achieve high thrust values. For bollard pull condition, the optimum proportions of the nozzle have been determined in earlier studies. One of the main parameters of the nozzle geometry is the outer nozzle diameter, and not only the propeller diameter. Provided that the hull lines and the nozzle are optimised for bollard pull, the main reason for the difference between calculated and measured bollard pull values is the cavitation behaviour of the nozzle and the propeller and their interaction.

As a result of cavitation tests it is possible to predict the risk of thrust breakdown caused by cavitation. For Kaplan propellers and propellers with diminishing chord length at the blade tip, the design engineer is now able to estimate the risk of thrust breakdown at a very early state of a project by means of the cavitation number σ_n and the torque coefficient $10K_Q$. In general the results show that propellers with Kaplan blade shape and outline are more advantageous for high blade loads, which are increasingly necessary because of the restricted draft of tug boats.

The final bollard pull result for the 220T AHT tug ***Janus*** confirms the preliminary estimation of the thrust breakdown by means of the correlation σ_n versus $10K_Q$, and also the implemented procedure with calculations and measurements at cavitation identity in order to be able to prepare a bollard pull prognosis with an accuracy in the region of 1 per cent.

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5. SYMBOLS

Ship

B	[m]	moulded breadth
F_D	[kN, t]	bollard pull
L_{OA}	[m]	length over all
MCR	[kW]	maximum continuous rating
P_B	[kW]	brake power
T	[m]	draught
t	[-]	thrust deduction factor

Ducted propeller

A_E	[m²]	expanded blade area
A_E/A_O	[-]	area ratio of the propeller
A_O, A_P	[m²]	propeller disc area
C_{TH}	[-]	thrust loading coefficient
d_h	[m]	propeller hub diameter
d_h/D	[-]	propeller hub diameter ratio
D	[m]	propeller diameter
D_A	[m]	exit diameter of the nozzle
D_E	[m]	entrance diameter of the nozzle
D_I	[m]	inner diameter of the nozzle
D_O	[m]	outer nozzle diameter
J	[-]	advance coefficient
K_Q	[-]	torque coefficient of the propeller
K_{TN}	[-]	thrust coefficient of the nozzle
K_{TP}	[-]	thrust coefficient of the propeller
K_{TT}	[-]	total thrust coefficient
L	[m]	length of the nozzle
n	[rps, rpm]	number of revolutions
P/D	[-]	propeller pitch ratio
P_D	[kW]	delivered power at propeller
Q	[Nm]	torque
R_n	[-]	Reynolds number
T_N	[N]	nozzle thrust
T_P	[N]	propeller thrust
T_T	[N, t]	total thrust, bollard thrust
x_P/L	[-]	position of the propeller in the nozzle
Z	[-]	number of blades
α_D	[-]	entrance cross-section ratio
β_D	[-]	exit cross-section ratio
η_i	[-]	ideal efficiency
η_0	[-]	open water efficiency
η_{PP}	[-]	pump efficiency
θ_{EXT}	[°]	skew angle at the projection
θ	[°]	rotation angle
ρ	[kg/m³]	mass density
σ_n	[-]	cavitation number

Indices

0	open water condition
0.7	radius r/R = 0.7
S	ship, prototype
M	model
min	minimum

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