INVESTIGATIONS ABOUT THE FORCES AND MOMENTS AT PODDED DRIVES

Hans-Jürgen Heinke, Potsdam Ship Model Basin (SVA), Germany

Abstract

Model tests with a four and a five bladed propeller in pull and push arrangement at a pod housing have been carried out. A z-drive dynamometer and a six-component balance were developed for the measurements in the towing tank and the large circulating and cavitation tunnel. The influence of the propeller hub geometry and of the interaction between the propeller and pod housing at the characteristics of the podded drives has been studied. The changing of the force and moment coefficients of podded drives with pull and push propellers have been calculated on the basis of systematic open water tests with different steering angles. For the prediction of the characteristic of the podded drive during crash stop manoeuvres tests with blocked propeller and tests at high advance coefficients are necessary. These tests have been carried out without and with cavitation.

1. Introduction

The interest in use of podded drives as the main propulsion system of ships is high due to the hydrodynamic characteristics and the advantages of the diesel-electric propulsion. The podded drives are integrated propulsion and steering systems. The knowledge of the relevant forces and moments at the podded drive at different steering angles is important for the design and optimisation of this system.

The ships are normally steered by turning the podded drives within $\psi = \pm 5°$. As long as the ship manoeuvres in the limits of these small steering angles the forces and moments of the podded drive and the cavitation behaviour of the propeller will be very close to that under straight ahead sailing conditions (steering angle $\psi = 0°$). The changing of the forces and moments becomes more significant at steering angles larger than $\psi = \pm 10°$. A critical ship manoeuvre for the podded drive is the crash stop with turning of the podded drive around the steering axis [1].

The relevant forces and moments of an azimuthing propulsion system at an angle ψ are the resulting thrust T_R, with its components T_X in longitudinal and T_Y in transverse direction relative to the ship's centre line, the propeller thrust T_P and the torque Q as well as the moment M_Z around the z-axis [2]. In addition information about the vertical force F_Z, the moments M_X, M_Y around the x- and y-axis are of interest for the integration of the podded drive in the aft ship. The vertical and horizontal propeller forces F_{YP}, F_{ZP} are important for the design of the bearings.

The calculation of the forces and moments at large steering angles is difficult. The inflow to the propeller, gondola and strut is changing with the steering angle. For larger steering angles there will be flow separation on the propeller blades, the gondola and the strut. So it is necessary to carry out model tests with different podded drives to get a data basis for the forces and moments at different steering angles [3]. The investigations with free running propellers [4] and z-drives [5], [6] are not adequate, because the dimensions and interaction effects between the pod housing and propeller are not considered in these tests.

2. Models of the podded drives

The propellers and the pod housing have been designed at the SVA Potsdam [7]. The propellers were designed such that a torque coefficient of $K_Q^* = 0.03489$ is available at advance coefficients near $J^* = 0.85$. The propellers with 4 and 5 blades should be useable as pull and push propeller at the pod housing. That's why it was decided to design the propellers with a cylindrical hub with $d_h/D = 0.2568$ and propeller blades without rake. The geometry of the hub was adapted to the pull and push propeller arrangement by special cone caps (see Figure 1). The tables 1 and 2 present the main data of the propellers and hubs.

Table 1: Propeller main data

Model propeller				CP 1374	CP 1375
Diameter	D	[m]	:	0.220	
Pitch ratio	$P_{0.7}/D$	[-]	:	1.1447	1.1130
Pitch ratio	P_{mean}/D	[-]	:	1.1138	1.0842
Expanded blade area ratio	A_E/A_0	[-]	:	0.81055	0.81094
Chord length	$C_{0.7}$	[m]	:	0.10025	0.08022
Hub diameter ratio (cyl. hub)	d_h/D	[-]	:	0.2568	0.2568
Skew angle	Θ_{eff}	[°]	:	24.2188	24.3317
Number of blades	Z	[-]	:	4	5
Direction of rotation				right-handed	

Table 2: Propeller hub geometry

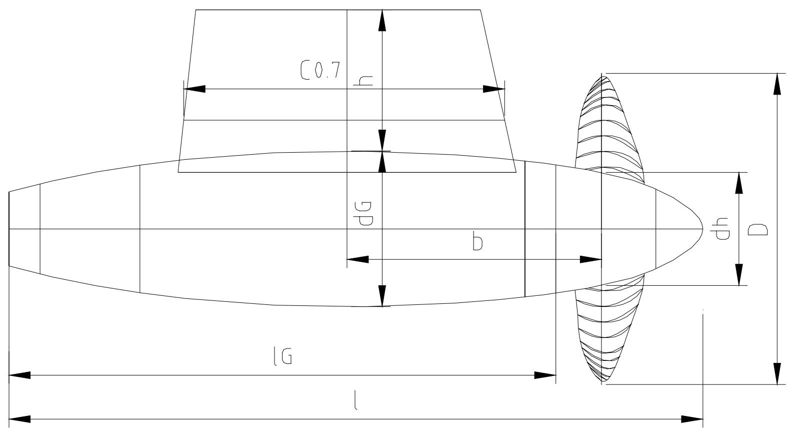
Hub length ratio	l_h/D	[-]	:	0.3193	
Hub diameter ratio	d_h/D	[-]	:	0.2568	open water test
Hub diameter ratio	d_h/D	[-]	:	0.3636	pull propeller arrangement
Hub diameter ratio fore	d_{hf}/D	[-]	:	0.2648	pull propeller arrangement
Hub diameter ratio aft	d_{ha}/D	[-]	:	0.4102	pull propeller arrangement
Hub diameter ratio	d_h/D	[-]	:	0.3530	push propeller arrangement
Hub diameter ratio fore	d_{hf}/D	[-]	:	0.4106	push propeller arrangement
Hub diameter ratio aft	d_{ha}/D	[-]	:	0.2899	push propeller arrangement

The geometry of the pod housing is simple (the strut is a NACA-profile, the gondola is an axial symmetrical body with the maximum diameter in the middle). The steering axis of the podded drive lies in the middle of the strut and gondola. The distance between the steering axis and the propeller plane of the pull and push propeller is nearly equal. The table 3 and the Figure 1 show the relevant parameters of the podded drives.

Table 3: Pod housing main data

Propeller arrangement				pull propeller	push propeller
Length ratio of the gondola	l_G/D	[-]	:	1.7557	1.7977
Total pod drive length ratio	l/D	[-]	:	2.2159	
Diameter ratio of the gondola	d_G/D	[-]	:	0.5000	
Clearance ratio between propeller plane and steering axis	b/D	[-]	:	0.8125	0.8352
Strut length ratio	$c_{0.7}/D$	[-]	:	1.0247	
Strut height ratio	h/D	[-]	:	0.4545	

Podded drive with pull propeller



Podded drive with push propeller

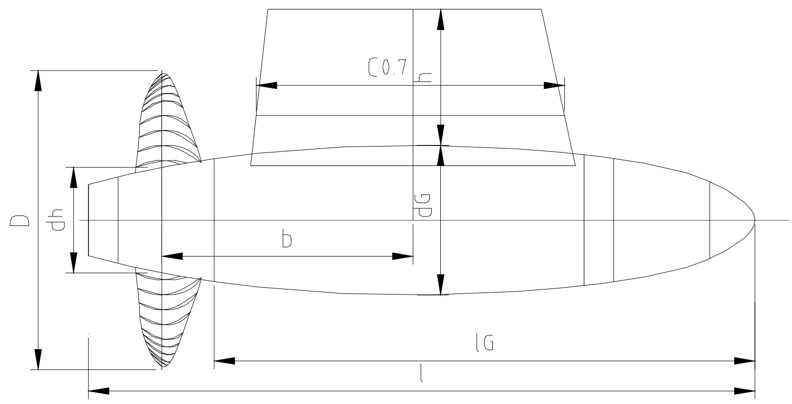


Figure 1: Geometric parameters of the podded drives

3. Test facility, measuring devices

The z-drive dynamometer Z600/4/1 has been developed and manufactured for the measurement of the propeller thrust and torque as well as the propeller forces in horizontal and vertical direction. The Figure 2 shows details of the measuring device. A cage with a special bearing is used for the measurement of the propeller forces F_{YP} and F_{ZP}. The construction of the propeller shaft, cage and bearing guarantees a minimum influence of the vertical and horizontal propeller forces at the propeller thrust and torque measurement.

The dynamometer Z600/4/1 measures the propeller thrust T_P, the propeller torque Q and the propeller forces F_{YP} and F_{ZP} in the system of co-ordinates rotating with the podded drive (propeller linked co-ordinates). The six-component balance R200 was especially designed and manufactured for the open water tests at different steering angles and the measurements at different steering manoeuvres in the towing tank of the SVA Potsdam and the large circulating and cavitation tunnel UT2 of the TU Berlin. The balance R200 is equipped with a rotary table. The propeller is powered by an electric motor installed above the rotary table. The balance measures the forces and moments of the podded drive in a ship-linked system of co-ordinates. The definition of the forces, moments and co-ordinates is given in Figure 3.

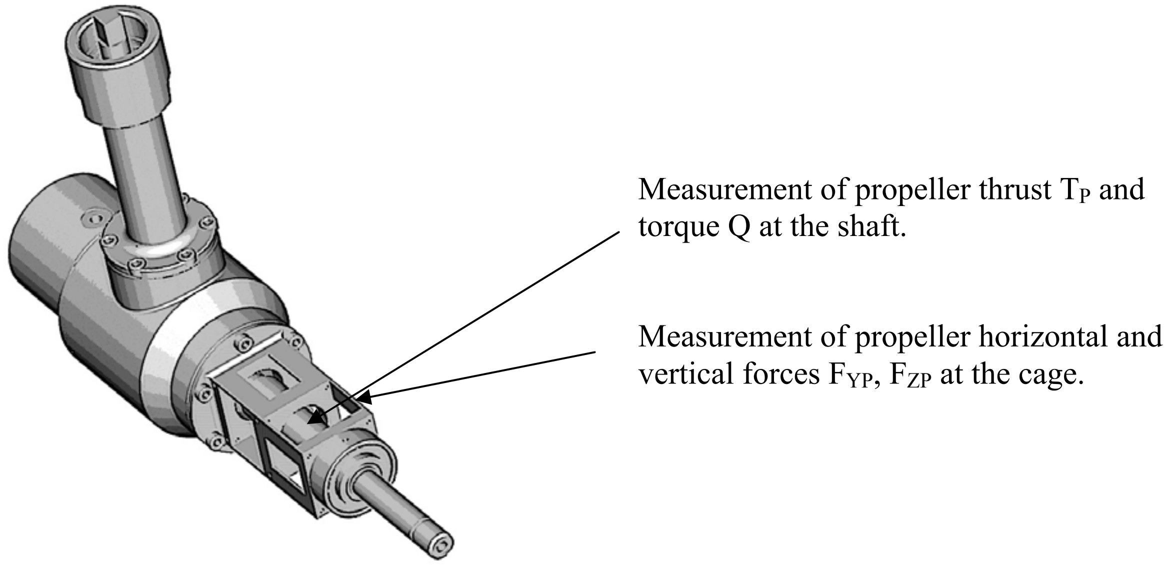
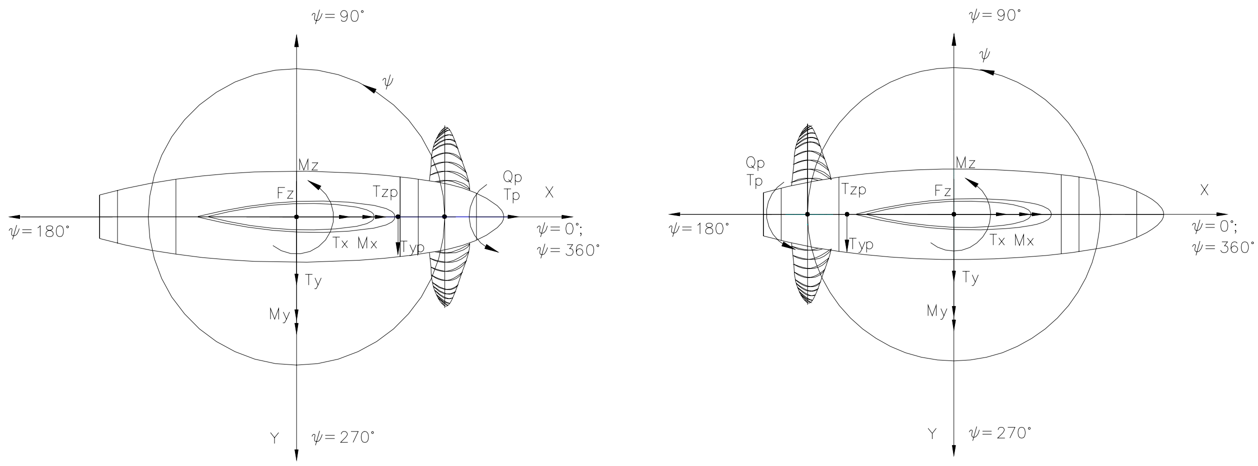


Figure 2: Dynamometer Z600/4/1



Pull propeller arrangement

Push propeller arrangement

Figure 3: Definition of forces, moments, co-ordinates

The following coefficients have been calculated:

Advance coefficient $$J = \frac{V}{n * D}$$

Propeller thrust coefficient $$K_{TP} = \frac{T_P}{\rho * n^2 * D^4}$$

Thrust coefficient of the pod housing $$K_{TPOD} = \frac{T_P * \cos(\psi) - T_X}{\rho * n^2 * D^4}$$

Longitudinal force coefficient $$K_{TX} = \frac{T_X}{\rho * n^2 * D^4}$$

Transverse force coefficient $K_{TY} = \frac{T_Y}{\rho * n^2 * D^4}$

Vertical force coefficient $K_{TZ} = \frac{F_Z}{\rho * n^2 * D^4}$

Resulting force coefficient $K_{TR} = \frac{T_R}{\rho * n^2 * D^4}$ $(T_R = \sqrt{T_X^2 + T_Y^2})$

Propeller torque coefficient $K_Q = \frac{Q}{\rho * n^2 * D^5}$

Propeller efficiency $\eta_0 = \frac{J}{2\pi} * \frac{K_{TP}}{K_Q}$

Efficiency in x-direction $\eta_X = \frac{J}{2\pi} * \frac{K_{TX}}{K_Q}$

Propeller thrust loading coefficients $C_{TP} = \frac{8}{\pi} * \frac{K_{TP}}{J^2}$

Moment coefficient around the x-axis $K_{MX} = \frac{M_{XB}}{\rho * n^2 * D^5}$ (M_{XB} calculated for a reference point)

Moment coefficient around the y-axis $K_{MY} = \frac{M_{YB}}{\rho * n^2 * D^5}$ (M_{YB} calculated for a reference point)

Steering moment coefficient $K_{MZ} = \frac{M_Z}{\rho * n^2 * D^5}$

Moment coefficient around the xy-axis $K_{MXY} = \frac{M_{XYB}}{\rho * n^2 * D^5}$ $(M_{XYB} = \sqrt{M_{XB}^2 + M_{YB}^2})$

Propeller transverse force coefficient $K_{FYP} = F_{YP}/T_P$

Propeller vertical force coefficient $K_{FZP} = F_{ZP}/T_P$

4. Open water characteristics

The open water characteristics of the propellers CP 1374 and CP 1375 were measured with and without pod housing. The Figure 4 shows the open water characteristics of both free running propellers fitted with a cylindrical hub. Especially in the design range there are similar thrust and torque coefficients (see also table 4).

The coefficients of the propeller in pull or push arrangement are influenced by the hub geometry (in comparison to the smaller cylindrical hub) and the interaction with the pod housing. The interaction effect is essentially based on the inhomogeneous flow distribution in the propeller plane, induced by the strut and gondola and the resulting pressure distribution around the pod housing. Additional the development of the propeller flow of a pull propeller is influenced by the pod housing.

The results of the open water tests with the propeller CP 1374 and CP 1375 in pull and push propeller arrangements are shown in the Figures 5 and 6. The table 4 presents the open water characteristics of the free running propellers and the podded drives in the design point with a propeller thrust loading coefficient of C_{TP} = 0.62 to 0.65. It can be seen, that the pull propeller arrangement is characterised by higher propeller and total thrust coefficients at equal torque coefficients. The result is a distinctly higher total efficiency for the podded drives with pull propellers.

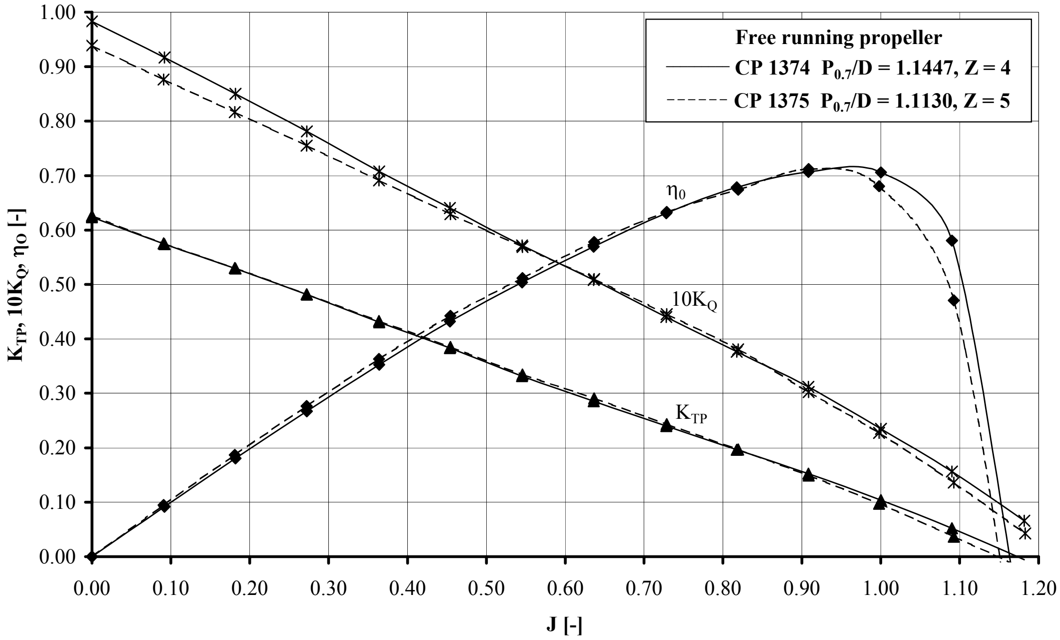


Figure 4: Open water characteristics of the free running propellers CP 1374 and CP 1375

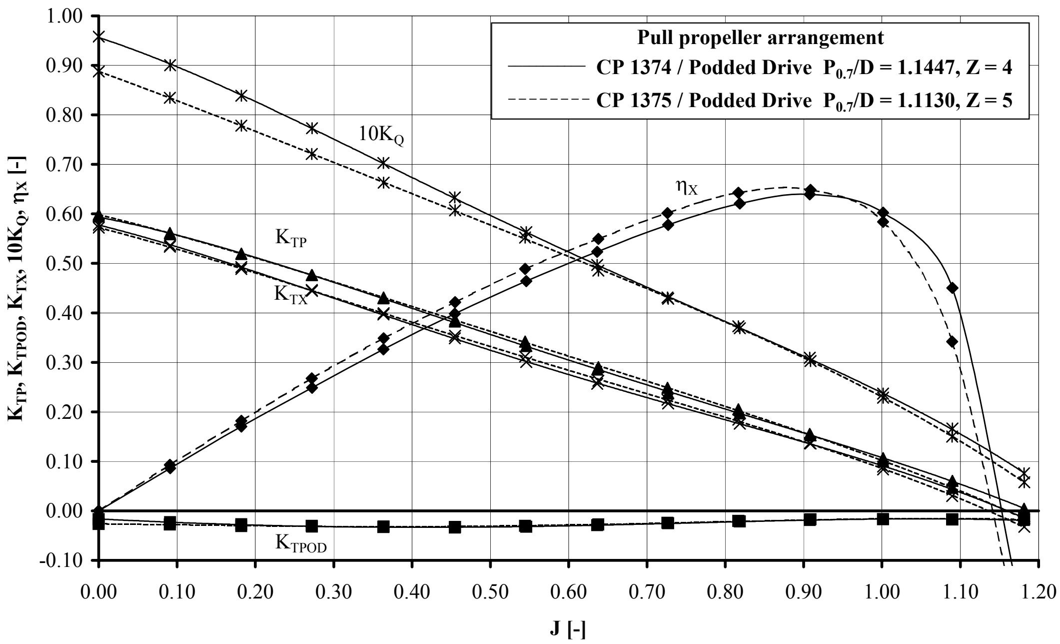


Figure 5: Open water characteristics of podded drives with pull propellers CP 1374 and CP 1375

The steering moment of the podded drives with a push propeller is distinctly lower than for the podded drives with a pull propeller (comparison for a constant distance ratio b/D between the propeller plane and the z-axis for both systems).

The rise in the number of blades from 4 to 5 results in a higher propeller and total thrust and in a small decrease of the pod housing resistance (propellers were designed for the same diameter and the same number of revolutions). The total efficiency of the podded drives in model scale with the five bladed propeller is about 3.4% higher for the pull propeller arrangement and about 5% higher for the push propeller arrangement. The interaction between the propeller and pod housing should be taken into account for the choice of the optimum number of blades. Investigations for podded drives for fast ships have for example shown, that also propellers with 6 blades should be considered [8].

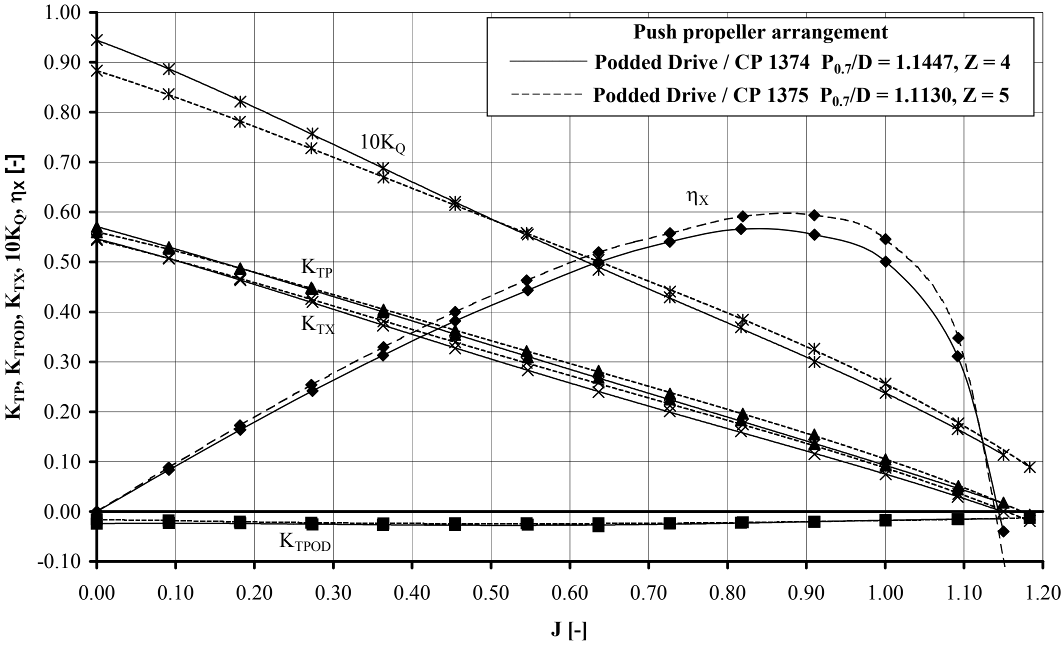


Figure 6: Open water characteristics of podded drives with push propellers CP 1374 and CP 1375

Table 4: Open water characteristics for the design torque coefficient, steering angle 0°

J	K_{TP}	K_{TPOD}	K_{TX}	K_{TY}	K_{TZ}	$10K_Q$	η_X	K_{MX}	K_{MY}	K_{MZ}	K_{FYP}	K_{FZP}
CP 1374 – free running propeller with cylindrical hub												
0.8551	0.1777					0.3489						
CP 1375 – free running propeller with cylindrical hub												
0.8549	0.1773					0.3489						
CP 1374 / podded drive – pull propeller arrangement												
0.8484	0.1824	-0.0208	0.1616	0.0272	-0.0085	0.3489	0.6255	0.0521	0.1133	-0.0198	0.0772	-0.0691
CP 1375 / podded drive – pull propeller arrangement												
0.8465	0.1877	-0.0202	0.1675	0.0331	-0.0060	0.3489	0.6466	0.0564	0.1177	-0.0245	0.0896	-0.0859
podded drive / CP 1374 – push propeller arrangement												
0.8398	0.1700	-0.0225	0.1475	-0.0075	0.0155	0.3489	0.5652	0.0371	0.1027	0.0041	0.0037	0.0246
podded drive / CP 1375 – push propeller arrangement												
0.8636	0.1727	-0.0220	0.1507	-0.0009	0.0145	0.3489	0.5938	0.0373	0.0929	-0.0001	-0.0094	0.0637

5. Forces and moments at different steering angles

The knowledge of the forces and moments at the propeller and podded drive at different steering angles is necessary for the design and optimisation of azimuthing propulsion systems.

Systematic tests with podded drives with pull and push propellers for the working conditions propeller with positive and negative rpm and with a trailing and a blocked propeller have been carried out to get data for the prediction of the forces and moments at different steering angles and manoeuvres as well as for the validation of CFD calculations. Only some results of the tests can be presented in this paper.

5.1 Open water tests with positive direction of rotation

Measurements for the podded drives with the propellers CP 1374 and CP 1375 in the pull and push propeller arrangement have been carried out at constant numbers of revolutions for the positive direction of rotation in the advance coefficient range J = 0 to J = 1.20. More than 24 steering angles were tested, so that on the basis of the polynomial coefficients for the open water characteristics the changing of the forces and moments with the steering angle can be calculated for each advance coefficient. The coefficients of the propeller and podded drive show a strong dependence on the propeller loading (flow velocity) and steering angle. The open water characteristics (coefficients = $f(J,\psi)$) are mostly irregular for the astern thrust conditions in the steering angle range 90° to 270° due to the flow separation at the propeller blades and the pod housing.

The Figures 7 and 8 show the force and moment coefficients of the podded drives at the design advance coefficient for the steering angles ranging from 0° to 360°. The influence of the propellers CP 1374 (Z = 4) and CP 1375 (Z = 5) at the force and moment coefficients is small for both propeller arrangements at the pod.

- Podded drives with pull propeller arrangement

The thrust and torque coefficients (K_{TP}, K_Q) of the pull propeller are increasing at steering angles larger than ±5°. The maximum propeller coefficients will be reached at the angles ±90°.

The longitudinal force coefficients (K_{TX}) are decreasing for both steering directions. The reduction of the longitudinal force is stronger for the steering direction, in which the propeller works against the oblique inflow (depending from the direction of rotation of the propeller). The longitudinal force coefficients are decreasing in the steering angle ranges ±90° with the increasing of the advance coefficient. The longitudinal force coefficients are negative in the steering angle range 90° to 270°.

For the podded drives with the pull propellers the zero transverse force can be found for a steering angle of about 2°. The transverse force coefficients (K_{TY}) are increasing with the steering angle. The maximum transverse force is reached at steering angles in the range ±60° to ±90°. For larger steering angles the transverse forces are decreasing.

The vertical force coefficients (K_{TZ}) are negative for steering angles of $0° \leq \psi \leq 150°$. In the steering angle range 180° to 360° the vertical force coefficients are positive at low advance coefficients and negative or nearly zero at larger advance coefficients.

The moments around the x- and y-axis (K_{MX}, K_{MY}) are depending from the longitudinal and transverse forces and the propeller torque. The maximum moments occur in the steering angle range ±80° to ±100°.

The steering moment coefficients (K_{MZ}) are increasing with the larger steering angles up to ±90°. For a further increase in steering angle up to ±180° a decrease in steering moment can be observed.

The coefficients of the propeller transverse and vertical forces (K_{FYP}, K_{FZP}) rise with larger steering angles. The maximum coefficients are reached in the steering angle ranges of ±30° to ±90°.

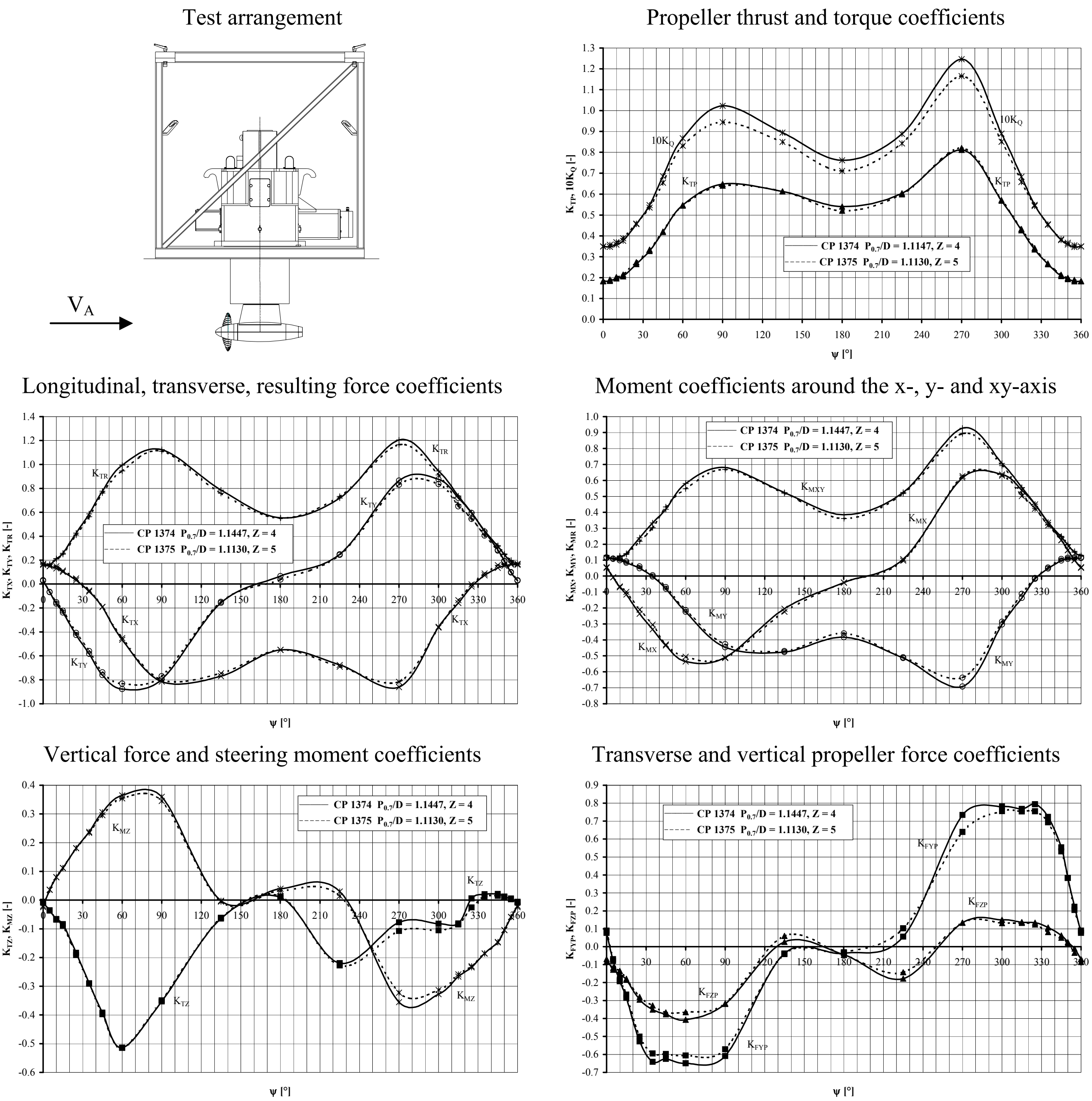


Figure 7: Force and moment coefficients of the podded drives with pull propeller, J = 0.847

- Podded drives with push propeller arrangement

The changing of the thrust and torque coefficients (K_{TP}, K_Q) of the push propeller are depending on the steering direction. The pod housing (especially the strut) in front of the propeller causes a twist in the propeller inflow, which increases or decreases the propeller loading. A twist in direction of propeller rotation leads to a reduction of the propeller coefficients for steering angles of $0° \leq \psi \leq 35°$. In the other steering direction the pre-twist against the propeller rotation leads to a rapid increase of the propeller coefficients. The maximum propeller coefficients will be reached in the angle ranges of $120° \leq \psi \leq 150°$ and $240° \leq \psi \leq 300°$.

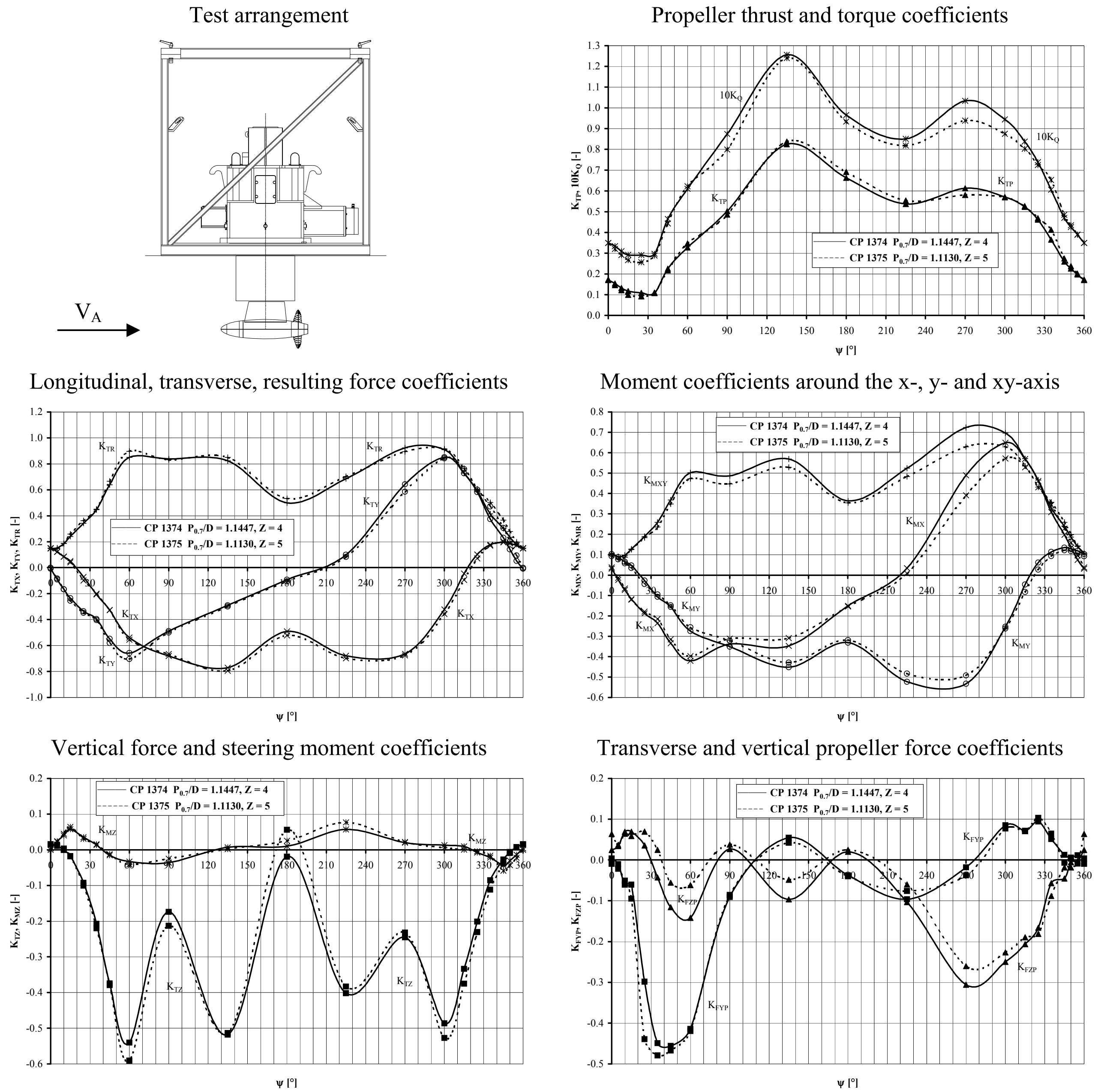


Figure 8: Force and moment coefficients of the podded drives with push propeller, J = 0.850

The longitudinal force coefficients (K_{TX}) are depending from the steering direction, similar to the propeller thrust coefficient. In the angle range of $0° \leq \psi \leq 30°$ the longitudinal force coefficients are increasing a little. For the other steering angles the longitudinal force coefficients are decreasing.

The transverse force is nearly zero at the steering angle $\psi = 0°$. The transverse force coefficients (K_{TY}) are increasing with the steering angle up to ±60°. For larger steering angles the transverse forces are decreasing.

The vertical force coefficients (K_{TZ}) are negative for steering angles larger than ±10°. The steering moment coefficients (K_{MZ}) for podded drives with push propellers are distinctly lower in comparison with podded drives with pull propellers. Also the coefficients of the propeller transverse and vertical forces (K_{FYP}, K_{FZP}) are smaller for the push propeller arrangement.

5.2 Open water tests with blocked propeller and at high advance coefficients

Ships with podded drives can stop by turning the pods around the steering axis from 0° to 180°. The number of revolutions has to be reduced during turning to avoid an overload of the electric motor. Characteristics of the podded drives for high advance coefficients are necessary for the prediction of the number of revolutions, forces and moments during a crash stop manoeuvre [1]. The number of revolutions can be reduced to zero during the turning, that's why tests with a blocked propeller are necessary.

The open water tests have been carried out in the towing tank of the SVA and in the large circulating and cavitation tunnel UT2 of the TU Berlin, to study the influence of cavitation on the forces and moments. The test section of this tunnel with a length of 11.0 m, a width of 5.0 m and a depth of 3.0 m allows tests with different steering angles. The Figure 9 shows the balance during the installation in the UT2. Measurements in the UT2 have been done for 24 steering angles at a constant water velocity and different numbers of revolutions ranging from $n_M = 0$ to $16\ s^{-1}$ at atmospheric pressure and at pressures corresponding to the model and full size cavitation numbers. In addition measurements have been carried out with different constant turning rates in the angle range from 0° to 180°, turning the pod inwards and outwards.

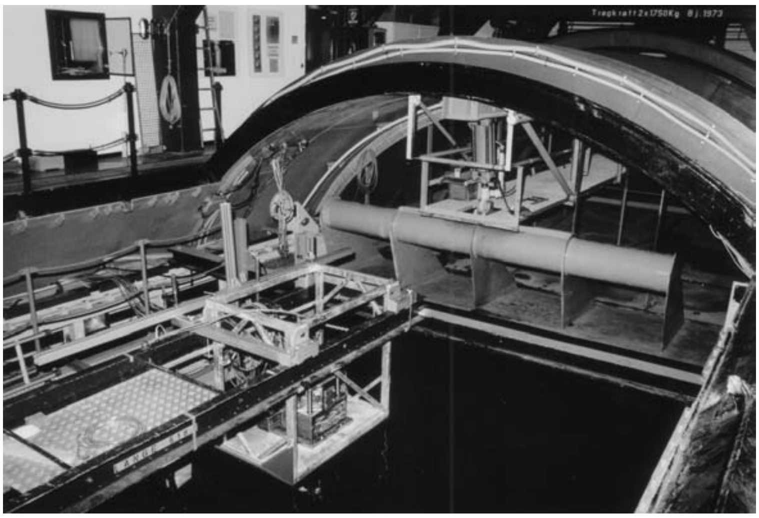


Figure 9: Large circulating and cavitation tunnel UT2 with the balance R200

- Blocked propeller ($n = 0\ s^{-1}$)

The Figure 10 shows measured forces and moments at the podded drive with the blocked pull propeller CP 1375. The influence of the direction of turning at the horizontal and vertical propeller forces is remarkable. An increase in turning rate from 30 to 40 degrees per second results in a small increase of the maximum forces and moments.

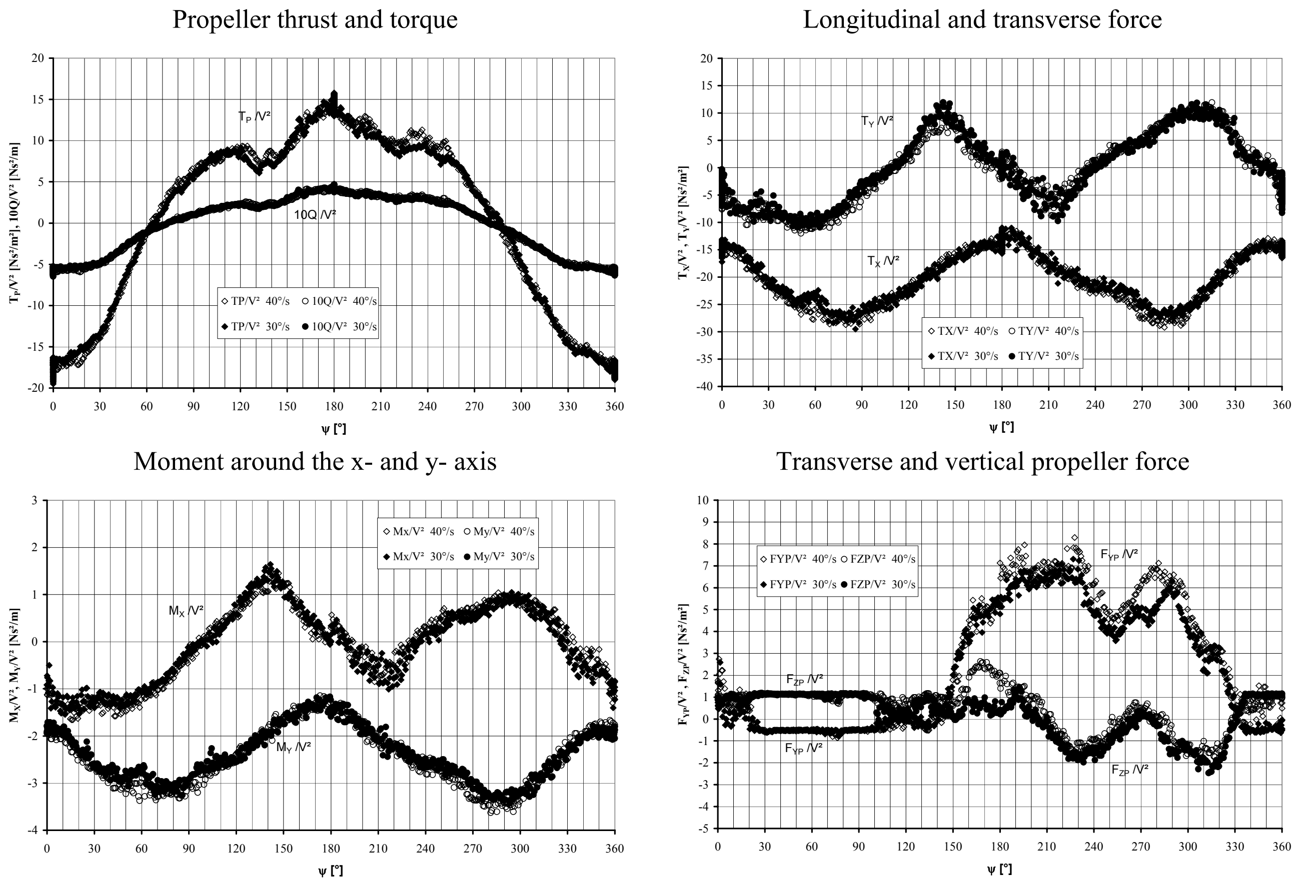


Figure 10: Forces and moments of the podded drive with the blocked pull propeller CP 1375, turning rate 30 and 40 degrees per second

- Propeller with low numbers of revolutions

Crash stops by turning the podded drives are often carried out at a constant torque. This implies a change in the number of revolutions during the turning. The propeller works than at high advance coefficient in the steering angle range ±45° to 180°. Results of systematic tests at high advance coefficients can be a basis for the prediction of the forces and moments during the turning with a constant torque.

The Figure 11 presents forces and moments at the advance coefficient $J = 2.62$ ($V_M = 2.306$ m/s, $n_M = 4\ s^{-1}$) at different steering angles. The comparison between the coefficients, measured in tests at different steering angles and in tests with a turning of the podded drive, shows, that the forces and moments especially in the cases with strong flow separation are higher at the dynamic measurements.

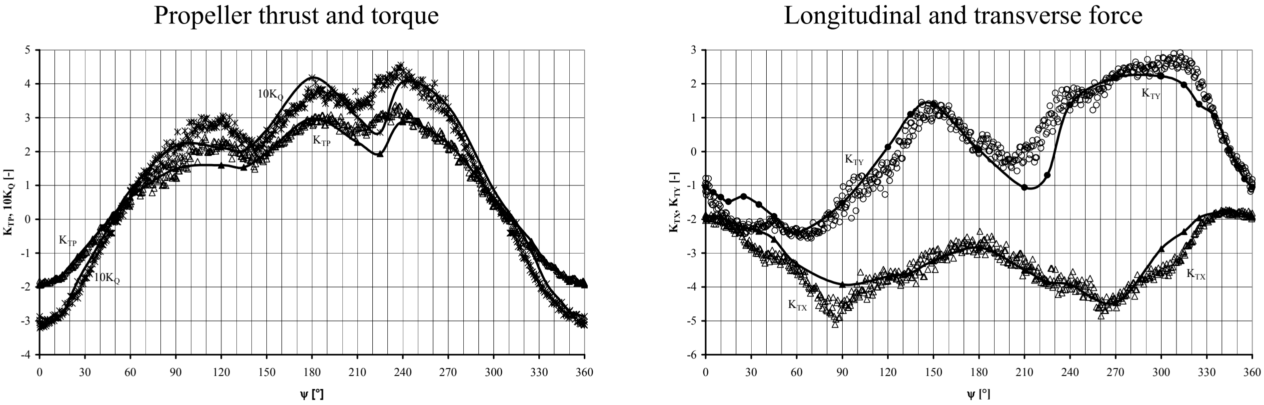
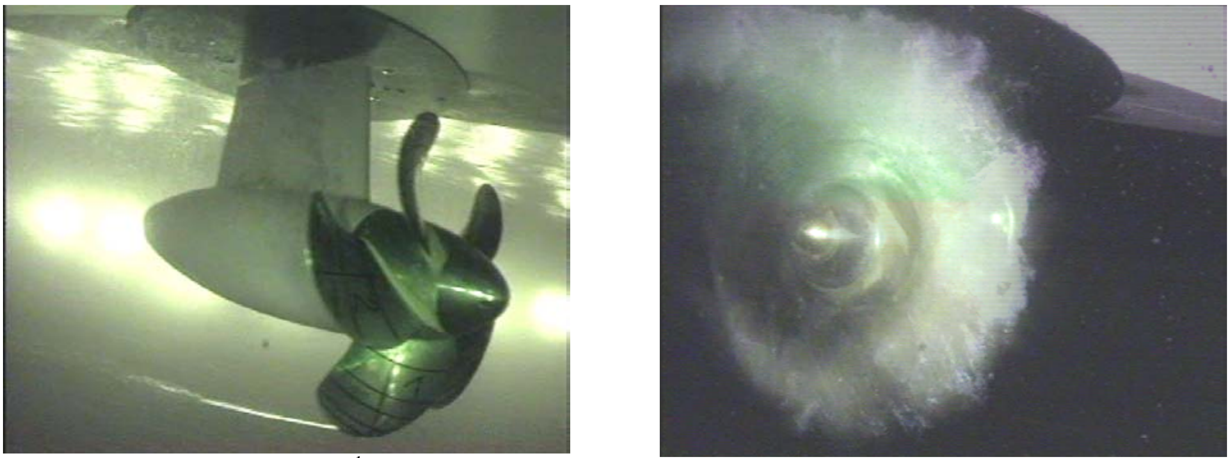


Figure 11: Forces and moments of the podded drive with the pull propeller CP 1375,
$J = 2.62$, $\sigma_V = 2.609$, measurements at different steering angles (connected points) and with a turning rate of 30 degrees per second (scatters)

- Influence of cavitation

The measurements with atmospheric pressure and the pressure for $\sigma_V = 2.609$ show, that the influence of the cavitation on the forces and moments at the blocked propeller ($n = 0\ s^{-1}$) is small. Only cavitating vortices occur at the propeller blades (Figure 12, left video print). The influence of the cavitation is also small at low numbers of revolutions (large advance coefficients), which are realistic for the different steering angles during the crash stop manoeuvre. Only in the angle range near ±90° a reduction of the forces due to cavitation at the propeller has been measured.



$V_M = 2.306$ m/s, $n_M = 0\ s^{-1}$, $\sigma_V = 2.609$ | $V_M = 2.306$ m/s, $n_M = 12.38\ s^{-1}$, $\sigma_V = 2.609$

Figure 12: Measurements at σ-identity

Measurements were also conducted with turning podded drives at the design speed and the design number of revolutions. A strong flow separation and cavitation lead to a reduction of the propeller thrust and torque at large steering angles in this case. The video print at the right side from Figure 12 gives an impression from the flow around the propeller in this unrealistic working condition (the torque of the propeller is distinctly above the available torque).

6. Conclusions

The propellers CP 1374 (four blades) and CP 1375 (five blades) have been designed for the same diameter and number of revolutions. The open water characteristics of both free running propellers are similar. The characteristics of the propellers are changing, if these working as pull or push propeller at a pod housing. The podded drives with the five bladed propeller in pull and push arrangement have the higher total efficiencies in comparison with the podded drives with the four bladed propeller.

The influence of a steering angle on the characteristics of podded drives with pull or push propellers is different. The thrust and torque coefficient of pull propellers are increasing at steering angles larger than ±5°. The thrust and torque coefficients of push propellers are depending from the turning direction in connection with the direction of propeller rotation in the steering angle range $0° < \psi < \pm 35°$.

The longitudinal force coefficients of podded drives with pull propellers are decreasing for both steering directions. The transverse force coefficients are increasing with the steering angle. The maximum transverse force coefficients are reached at steering angles in the range of ±60° to ±90°.

The longitudinal force coefficients of podded drives with push propellers are depending from the turning direction, similar to the propeller coefficients. The transverse force coefficients are increasing with the steering angle. The maximum transverse force coefficients will be reached at $\psi = \pm 60°$.

The steering moment coefficients of podded drives with push propellers are distinctly lower than for podded drives with pull propellers.

Force and moment measurements have been carried out at constant steering angles and in tests with a turning of the podded drive. The forces and moments at the podded drives are larger in steering angle ranges with a strong flow separation, if the podded drive is turning. The increase of the turning rate leads to a small increase of the maximum forces and moments.

The influence of cavitation on the forces and moments of a blocked propeller and a propeller with low numbers of revolutions is small.

Acknowledgements

The author would like to express his gratitude to the Federal Ministry of Economics and Labour for the support of the research project about the forces at podded drives.

References

[1] Boushkovsky, V.; Poustoshny, A.; Vasiliev, A.; Veikonheimo, T.
A Crash-Stop Study for an Azipod-Propelled Vessel
FAST 2003, Ischia (Italy), Oct. 2003

[2] Brix, J.
Manoeuvring Technical Manual
Seehafen Verlag GmbH, Hamburg, 1993

[3] Grygorowicz, M.; Szantyr, J.
Hydrodynamic Model Experiments with Pod Propulsors
HYDRONAV'2003, Gdansk, Oct. 2003

[4] Binek, H.; Müller, E.
Steuerpropeller
Schiff & Hafen, Heft 12/1975

[5] Lebedew, S. P.; Perschitz, R. Ja.; Rusezkij, A. A.; Awraschow, N. S.; Tarasjuk, A. B.
Sredstwa aktiwnogo uprawlenija sudami
Sudostroenie, Leningrad, 1969

[6] Wojtkynskogo, Ja. I.
Sprawotschnik po teorij korablja - Yprawljaemost wodismestschajustschich sudow - Gidrodinamika sudow s dinamitscheskimi prinzipami poddershanija
Sudostroenie, Leningrad, 1985

[7] Heinke, H.-J.
Hydrodynamische Dimensionierungslasten für Podded Drives
Bericht Nr. 2946, Schiffbau-Versuchsanstalt Potsdam, März 2004

[8] Heinke, C.; Heinke, H.-J.
Investigations about the Use of Podded Drives for Fast Ships
FAST 2003, Ischia (Italy), Oct. 2003