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Research Article

Determining the loss of efficiency of twin propeller systems in circulation maneuvers

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Abstract

Nowadays, a large number of newly-built inland and navy vessels are equipped with a twin propeller-twin rudder configuration (TPTR). Observations of units of TPTR systems when performing maneuvers at curvilinear trajectories show asymmetrical loading. The nature and parameters of the phenomenon have not been sufficiently studied, in which specific maneuvers could lead to overloading and loss of effectiveness. The purpose of this paper is to study the effectiveness of a ship's TP system in maneuvering, taking into account the influence of the oblique flow to the "internal" and "external" propellers respective to the trajectory of motion. Appropriate maneuvering experiments with a free-running ship model are carried out, by which the propeller thrust and torque are measured. Based on the obtained investigation results, analyses of interaction effects in the TP system are performed. Coefficients for estimating the asymmetric efficiency of the twin-screw system are developed, and related conclusions are summarized.

1. Introduction

Nowadays, large numbers of inland and navy vessels are equipped with a twin propeller-twin rudder configuration (TPTR). Furthermore, TPTR has been applied to large seagoing ships in order to enhance performance in maneuvering, especially in shallow water. Observations of the work modes of propellers and rudders when performing maneuvers at curvilinear trajectories show asymmetrical loading. The nature and parameters of the phenomenon have not been sufficiently studied, in which specific maneuvers could lead to loss of effectiveness in some of the units of a TPTR system (Khanfir et al., 2012; Molland & Turnock, 2007; Viviani et al., 2007; Ortolani et al., 2020).

In NATO Research Units, criteria and standards for the manageability of this ship type have been extensively developed (ANEP-70 Volume I, 2003). However, no particular attention has been paid to the behavior of the ship type's propulsion and steering systems during maneuvering (Fossen, 2005; Goodman et al., 1976). The phenomenon can lead to overloading during tight maneuvers, like increased shaft torque, up to and above the nominal values and, of course, to a significant imbalance (Coraddu et al., 2013; Dubbioso & Viviani, 2012a; Dubbioso & Viviani, 2012b; Efremov, 2016; Efremov & Milanov, 2017). This can be potentially dangerous, especially in the case of complex ship propulsion configurations, like shafts powered via a unique reduction gear (Dubbioso et al., 2011).

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The purpose of the research is to study the effectiveness of a ship's TP system in maneuvering, taking into account the influence of the oblique flow to the "internal" and "external" propellers respective to the trajectory of motion.

To investigate deeply the phenomena of asymmetric load, appropriate maneuvering experiments with a free-running ship model are carried out, by which the propeller thrust and torque are measured. Based on the obtained investigation results, analyses of the interaction effects in the TP system are performed. Coefficients for estimating the asymmetric efficiency of the units of the twin-screw system are developed, and related conclusions are summarized.

2. System model of the interaction of the propellers of TPTR systems in ship maneuvers

2.1 Characteristics of the single propeller in maneuvering

When a ship moves with a straight course with nominal propeller revolutions n_0 and nominal speed V_0, this mode is fully characterized by the advance coefficient $J_0=V_0.(1-w)/D.n_0$ and the thrust and torque coefficients K_{T0}, K_{Q0}, respectively:

$$K_T = \frac{T}{\rho n^2 D^4}$$ - thrust coefficient, (1)

$$K_Q = \frac{Q}{\rho n^2 D^5}$$ - torque coefficient. (2)

Upon entering a curvilinear manoeuvre, conditions into the propeller's zone are changed- the ship's propeller works in an oblique stream flow. In 1964, research on a propeller in free water at an oblique flow in the angle range $0° \leq \beta_k \leq 30°$ was published by Gutshe (Dubbioso & Viviani, 2012a; Efremov, 2016; Gutshe, 1964). Detailed analysis of the data was carried out by Goffman. In the case of a curvilinear motion with a drift angle β, the character of the hull streamflow varies, respectively, the wake fraction w. As the local drift angle β_K increases, w decreases and reaches zero at limit values of the β and angular speed $\overline{r}$ (Basin, 1977; Fedyaevsky & Sobolev, 1963; Goffman, 1988; Vasiliev, 1989):

$$w' = w.f(\beta, \overline{r}) ,$$ (3)

β, $\overline{r}$ - Drift angle and angular velocity, respectively.

2.2 Characteristics of the propellers of twin screw ships in maneuvering

The asymmetric thrust and torque load of twin-screw ships could be explained by the change of the local drift angle β_K and wake fraction w. During motion of a multiple screw vessel in a curved trajectory, the local drift angle into the rudder and propeller zone, particularly for twin screw ships, is different because of the radii of rotation according to the center/e of turning, due to the propeller position along the ship (Efremov, 2016; Efremov, 2015; Vasiliev, 1989; Voitkunsky, 1982).

The influence of β to w fundamentally differs for both sides. The wake fraction w depends on the advance coefficient J and the thrust and torque coefficients K_T, K_Q. The wake fraction w in the system "propeller shafts - steering gear" is asymmetric if it is considered separately for each propeller's area. In a curvilinear motion, the velocity vectors V_{port}, V_{sb} at the corresponding point of the propeller's location is important, and is affected by the angular velocity (**Figure 1**) (Efremov, 2016; Vasiliev, 1989):

$$r = \frac{V}{R}$$ (4)

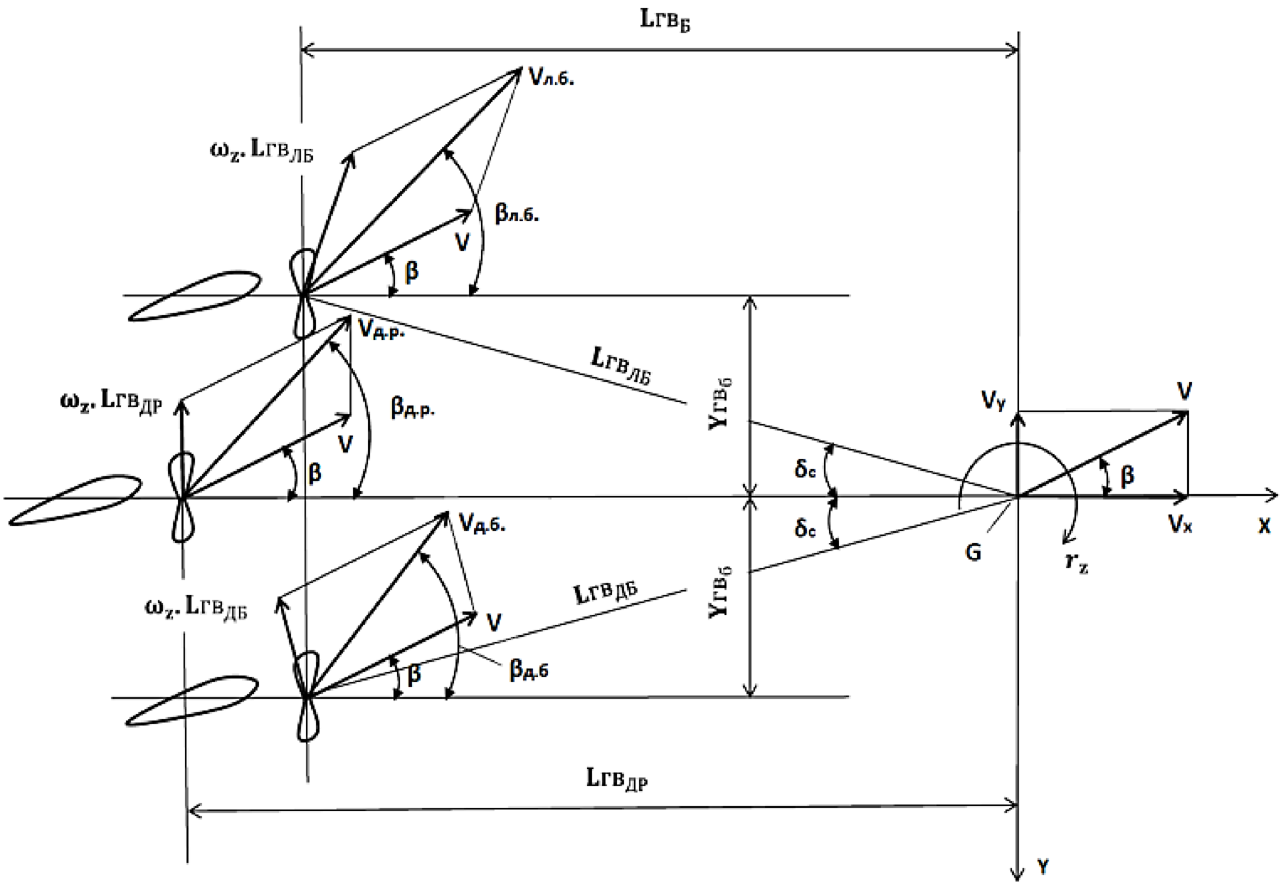

Figure 1 Interaction between velocity vectors at boards and angular velocity, ship speed at center of gravity, and local drift angles (Efremov, 2015).

The determination of the local drift angle β_k and local velocity V_{mid} to a propeller located in the middle line plane was descibed by Basin (1977). At a location different from the middle plane, like in TPTR ships, the values of β_k are modified and must take into account the propellers shifting location. This distance is determined by the angle δ_c (**Figure 1**). Thus, the preceding equations are modified:

$$\beta_k^{p,sb} = \frac{\beta + |r_z|.\left|L_R^{p,sb}\right|}{1 \pm |r_z|.\left|Y_R\right|} \tag{5}$$

The expression for the velocity at the point where the propeller is located laterally (on-board) is prepared analogously:

$$V_R^{p,sb} = V\sqrt{1+\left|r_z\right|.\left|L_R^{p,sb}\right|.(2.(\beta+\delta_c)+\left|r_z\right|.\left|L_R^{p,sb}\right|)} \tag{6}$$

Through the above described formulas, it is possible to determine the wake fraction w' and the influence of the local drift angle to the efficiency for each unit of the TPTR system when performing curvilinear maneuvers (Efremov, 2015; Vasiliev, 1989).

3. Investigation of the asymmetric behavior of the units of a TP system by free-running model maneuvering tests

3.1 Experimental matrix with measurement of the propeller's thrust and torques of a TPTR system

The dynamics of the Engine-Hull-Propeller system can be modelled in 3 scenarios - keeping the RPM constant or the shaft torque and the latter is to model the engine output power. In practice, the most common are two types of propulsion plant- one prime mover, which through a unique reduction gear powers the screw's shafts, and one which has 2 separate prime movers to each screw's shaft. For a setting with a unique reduction gear, there is a significant possibility of unbalanced loads during curvilinear tight maneuvers; in this case, it would be impossible to isolate the asymmetrical loads for each of the two propellers (Dubbioso et al., 2011). These considerations led to the choice of a simplified set-up with a twin system "Engine-Propeller". Both engines were set to maintain the desired revolutions corresponding to the required advance speed and, by dynamometer, the load of the "internal" and "external" screws was monitored.

The experimental program included standard maneuvers at speeds at which the units of the TPTR system were subject to heavy loads; the asymmetrical load could be determined. Since the measurements were taken on the shaft of one of the two screws, the circulation maneuvers of the experimental program were provided for both boards. Thus, it appeared to be "external" or "internal" located.

Table 1 Test matrix.

Maneuver	Model initial speed [m/s]	Fr [-]	Rudder angle [deg]
Turning	1.9 ; 2.48	0.34 ; 0.44	±25, 30, 35

Ship model

A fast TPTR ship model was used for the investigations. It was designed and produced at BSHC. Model hull main particulars are given in **Table 2**, and a 3D hull view in **Figure 2**.

Table 2 Main particulars of hull.

Non-dimensional hull data	Symbol	Values
Length to beam ratio	L_{PP}/B	6.269
Beam to draft ratio	B/T	3.395
Rudder lateral area	A_R/LT	0.011
Block coefficient	C_B	0.460
Number of propellers	[–]	2
Number of rudders	[–]	2

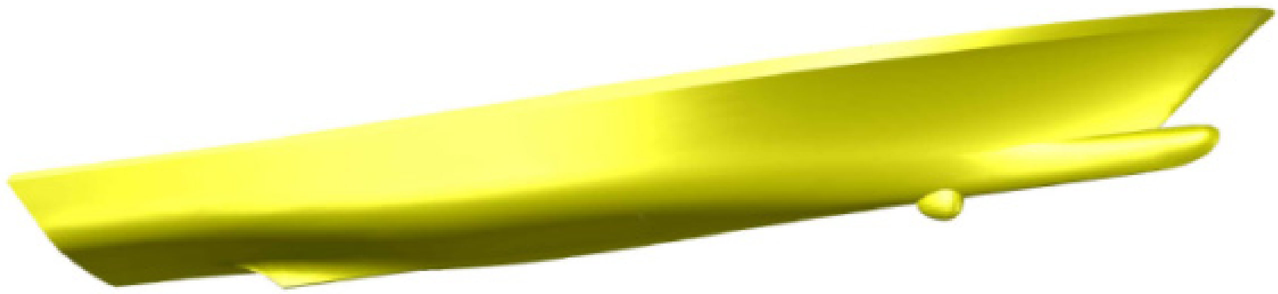

Figure 2 3D hull model view.

The ship model was equipped with stock propellers (**Figure 3** and **Table 3**).

Table 3 Propeller model data.

Propellers	**№1/№2**
Propeller diameter, mm	110.3
Design pitch ratio at 0.7R	1.04
Expanded blade area ratio	0.446
Number of blades	4
Direction of rotation	inward

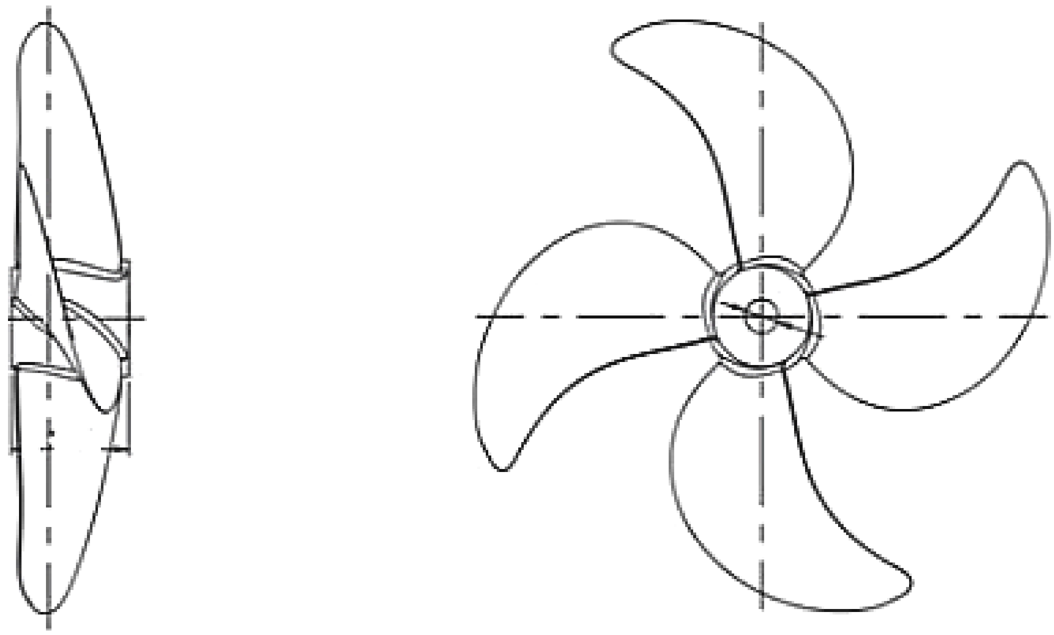

Figure 3 Propeller view.

The model was equipped with two rudders with characteristics and geometry as in **Table 4**, **Figure 4**. The propeller-rudder arrangement of the ship model is illustrated in **Figure 5**.

Table 4 Rudder model data.

Characteristic	Symbol	Dimension	Model
Area	A_R	m^2	0.00545
Height	h_R	m	0.1016
Mean chord	b_R	m	0.0537
Profile		NACA 0019	

Figure 4 Rudder geometry.

Figure 5 View of rudder- propeller arrangement.

The maneuvering model tests were carried out at BSHC Manoeuvring & Seakeeping Basin (**Figures 6** and **7**) at an initial steady speed, deep calm water, and constant revolutions.

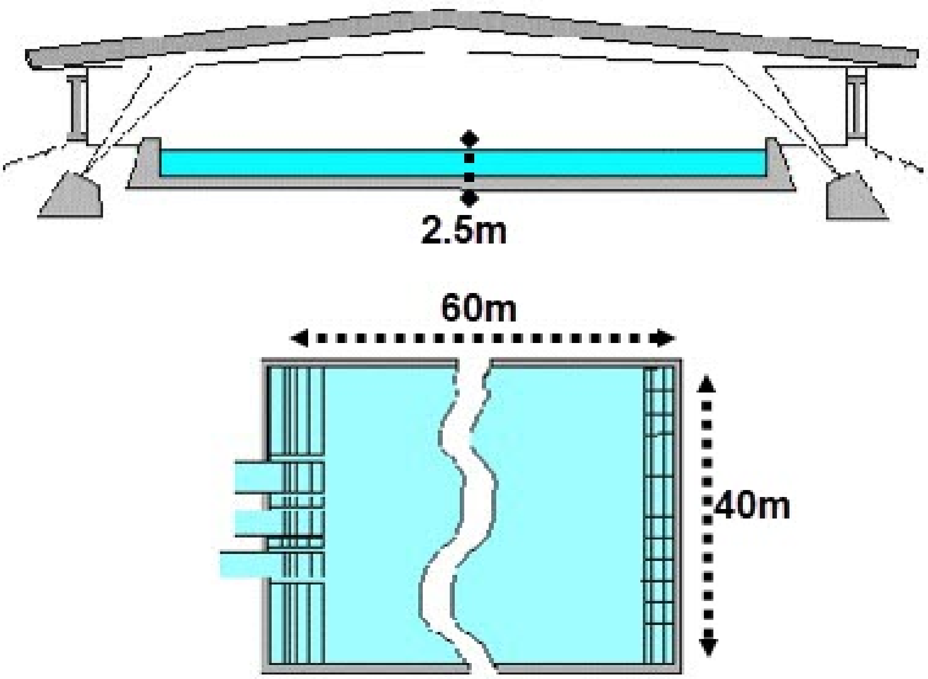

Figure 6 BSHC Manoeuvring & Seakeeping Basin main dimensions.

Figure 7 BSHC Manoeuvring & Seakeeping Basin.

Model equipment

The equipment for the free-running tests was physically divided into 2 groups, on-board and onshore equipment, synchronized by a radio link. The on-board equipment contained all necessary units for remote controlling of the model, as well as for measurements, data acquisition, and data recording on-board and onshore (**Figure 8**).

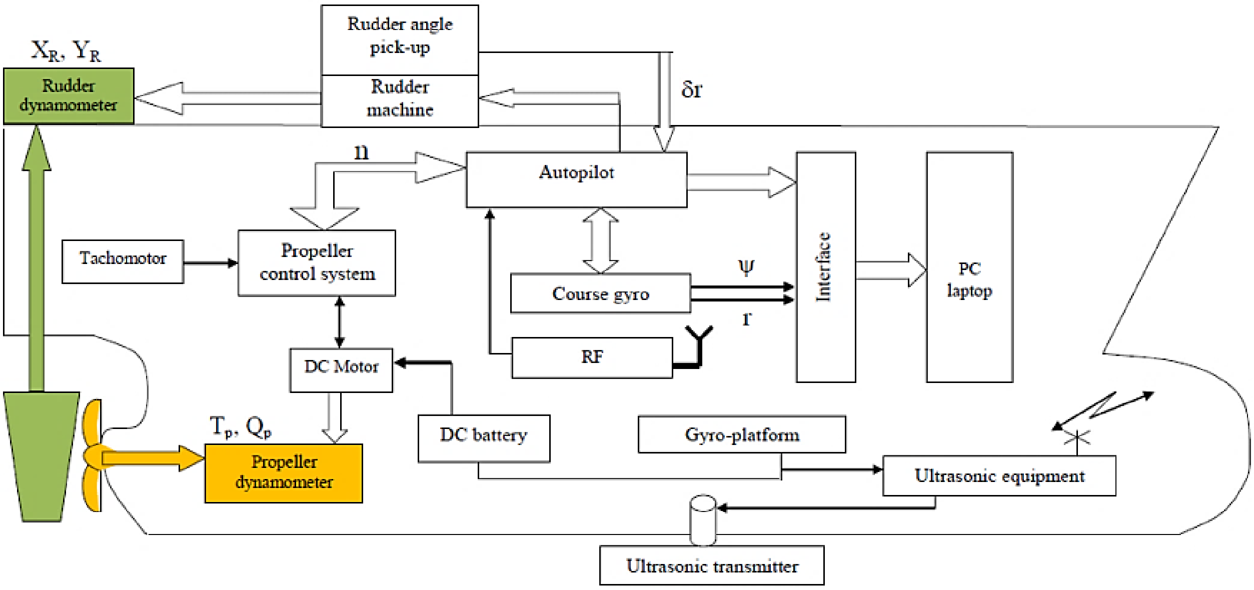

Figure 8 Model equipment block-scheme.

3.2 Experimental results for the asymmetric efficiency of the units of twin propellers by free-running model maneuvering tests

The following figures summarize the results of the performed tests of the measured thrust and torque (**Figures 9** and **10**) of both propellers during turning circle maneuvers (Efremov, 2016).

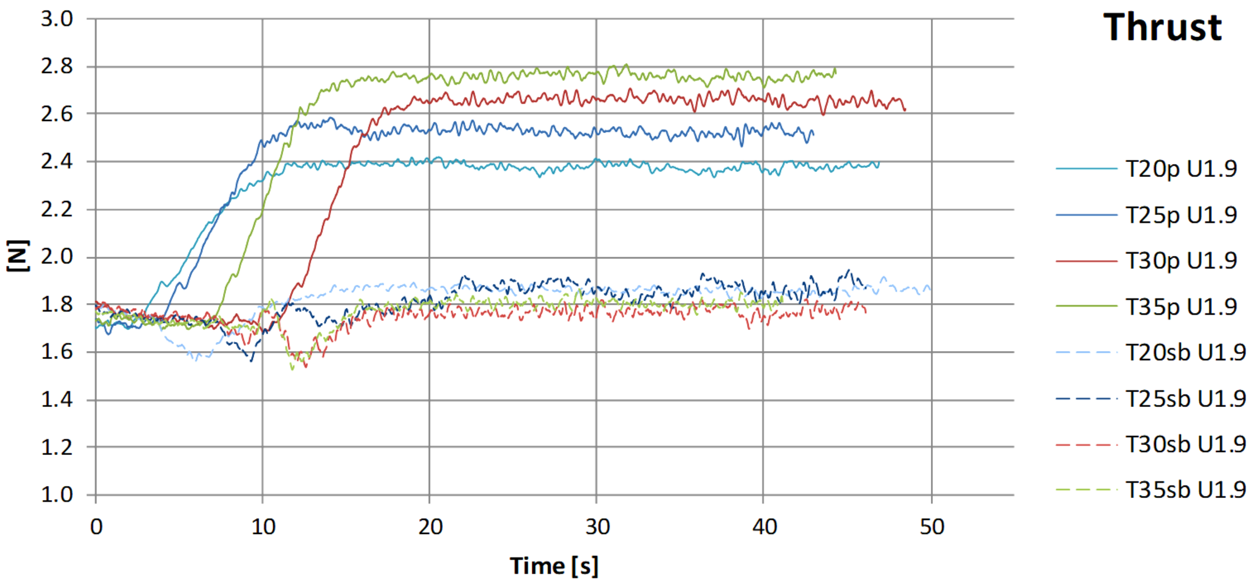

Figure 9 Thrust [N] of “external” and “internal” (dashed) propellers in turning circle maneuvers with U = 1.9 m/s.

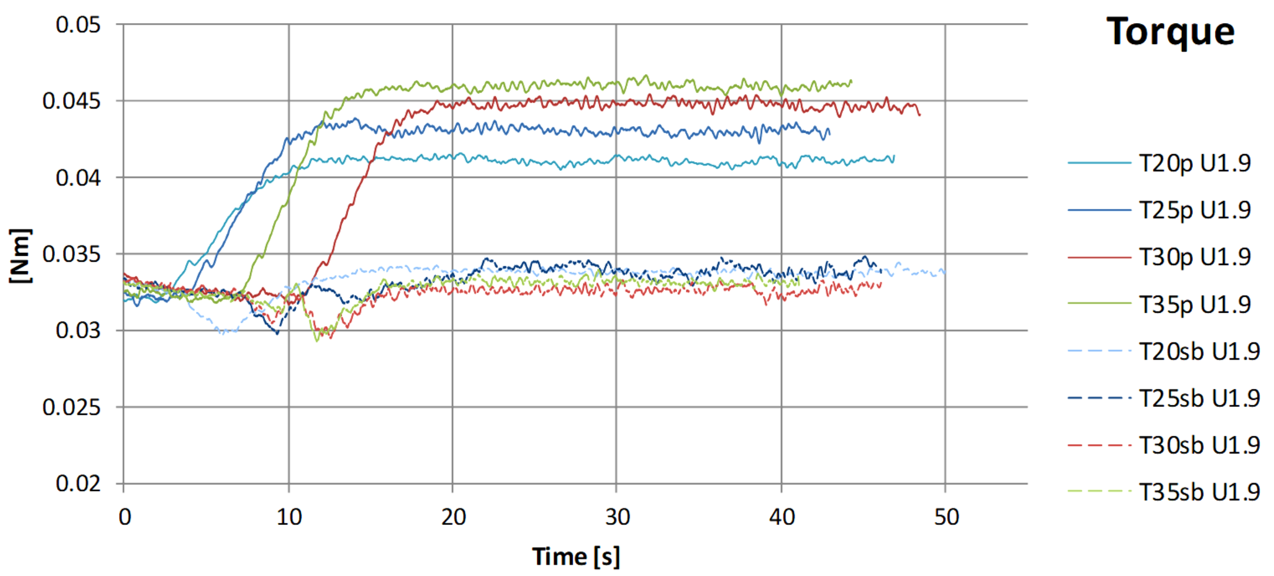

Figure 10 Torque [Nm] of "external" and "internal" (dashed) propellers in turning circle maneuvers with U = 1.9 m/s.

The summary graphs show large increases of the load of the "external" screw when entering circulation, independent of the rudder angle. It is clearly expressed, according to the angle of attack of the streamflow, caused by the angle of deflection of the rudder. The variation of the thrust and torque of the "internal" screw compared to that of the "external" is difficult to distinguish, irrespective of the local angle of attack.

4. Determination and analysis of the hydrodynamic interaction coefficients of the TRTP system

In the summarized graphs of the measured thrust and torque of the internal and external propellers during turning circle maneuvers, the large overload to the external propellor can be clearly noted. When the rudder angle increases, the thrust and torque load of the external screw increases too, while the internal one has slight changes in its characteristics. It is also noticeable that the "internal" screw in the steady stage of circulation is slightly overloaded too- approximately 8 % (**Figure 13**).

The overload of the external screw according to the initial phase of the maneuver is observed by its proportionality thrust and torque increasing, and is different for both speeds. However, the "internal" screw is slightly unloaded, irrespective of the model speed (Efremov, 2016).

The mutuality between the thrust and torque of the propellers can be seen from the following graphs showing the relative torque variation to the same angles of rudder deflection.

The derivative of the relative thrust and torque overload to the angle of rudder deflection is linear, in this case.

Based on the presented linear derivatives, an attempt could be made to predict the possible overload in an oblique flow, which could lead to critical situations. For this purpose, simplified coefficients are formulated:

$$q_T^{p,s\,'} = \frac{d\Delta T}{d\delta} \tag{7}$$

$$q_Q^{p,s'} = \frac{d\Delta Q}{d\delta} \tag{8}$$

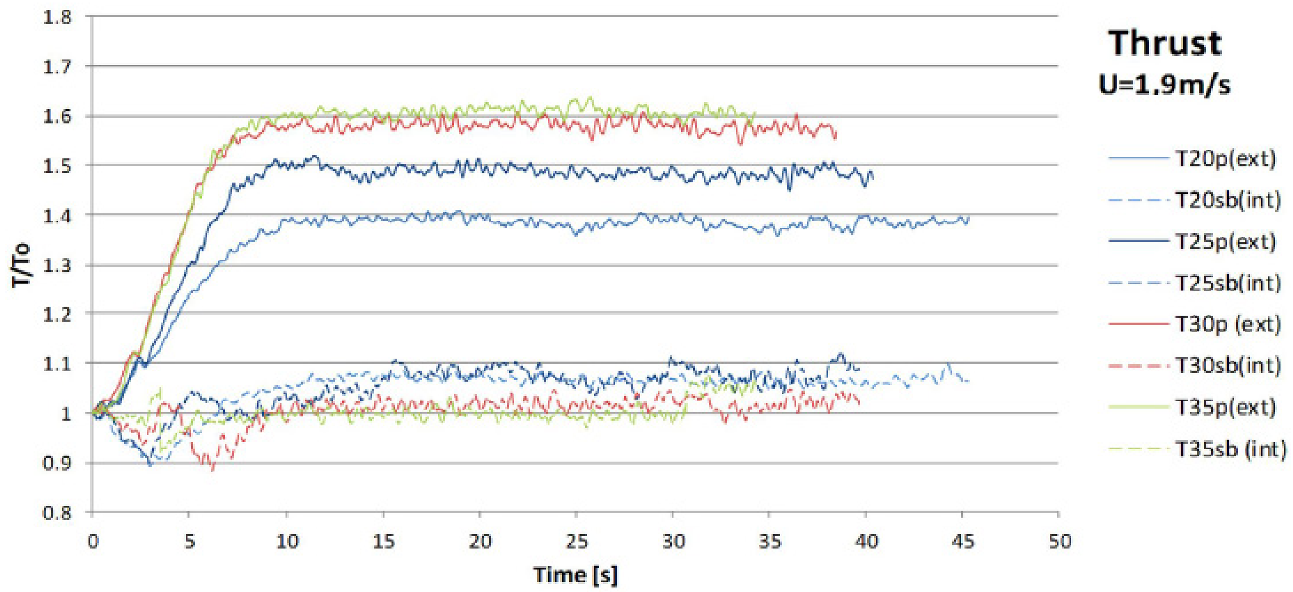

Figure 11 Relative thrust variation respective to initial value at each propeller of twin screw in turning circle maneuvers.

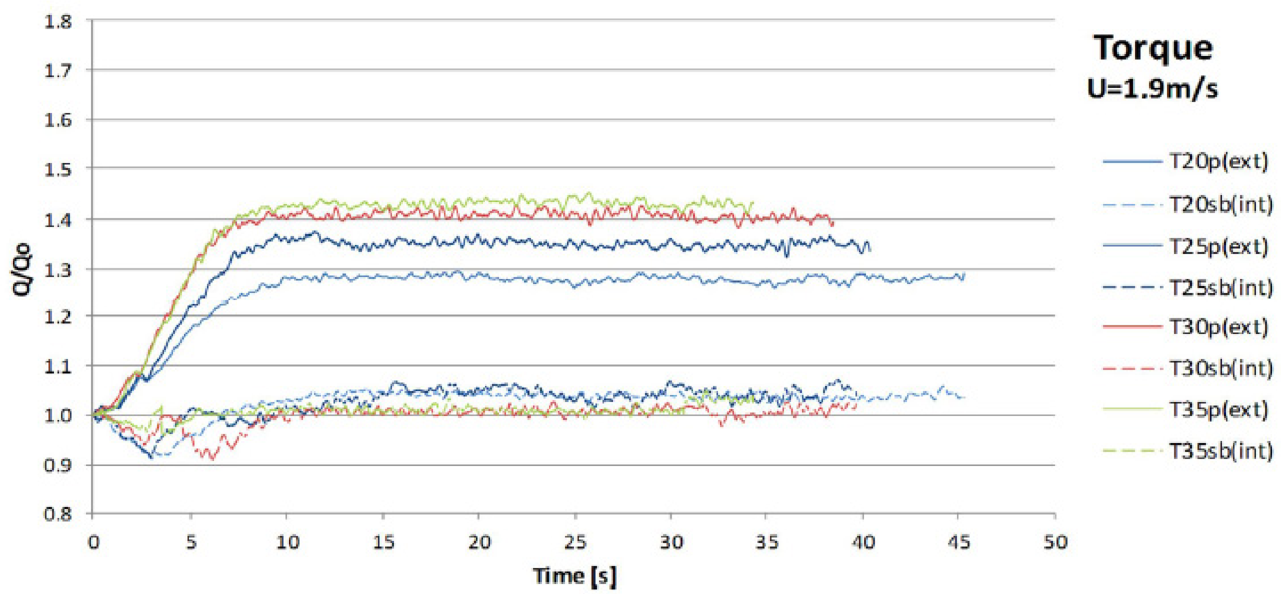

Figure 12 Relative torque variation respective to initial value at each propeller of twin screw in turning circle maneuvers.

5. Conclusions

The study shows an asymmetric efficiency of the screws of a TPTR system in curvilinear maneuvers. External locations, according to the side on which the curvilinear maneuvers are performed, are in risk of possible overload or loss of efficiency;

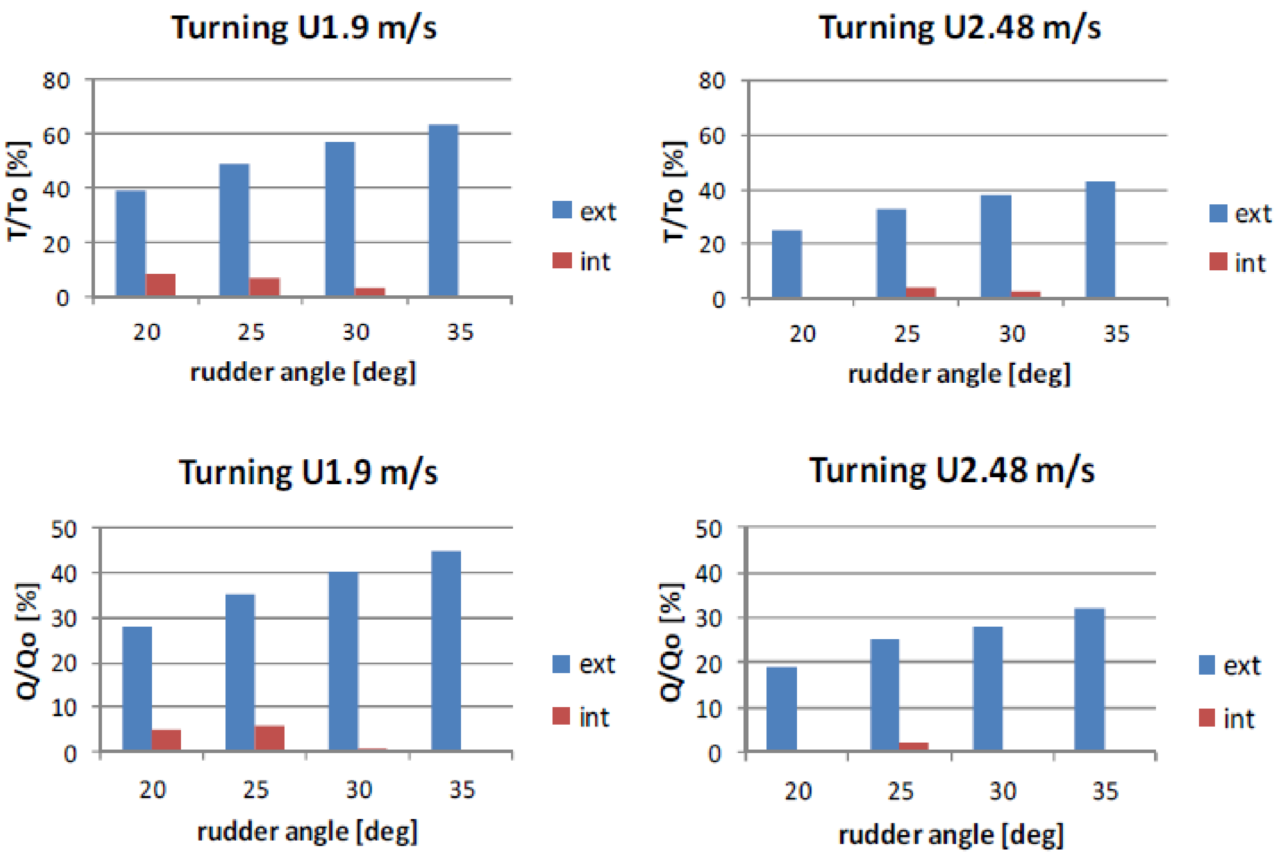

Figure 13 Steady relative torque overload for both screws at low and high model speeds.

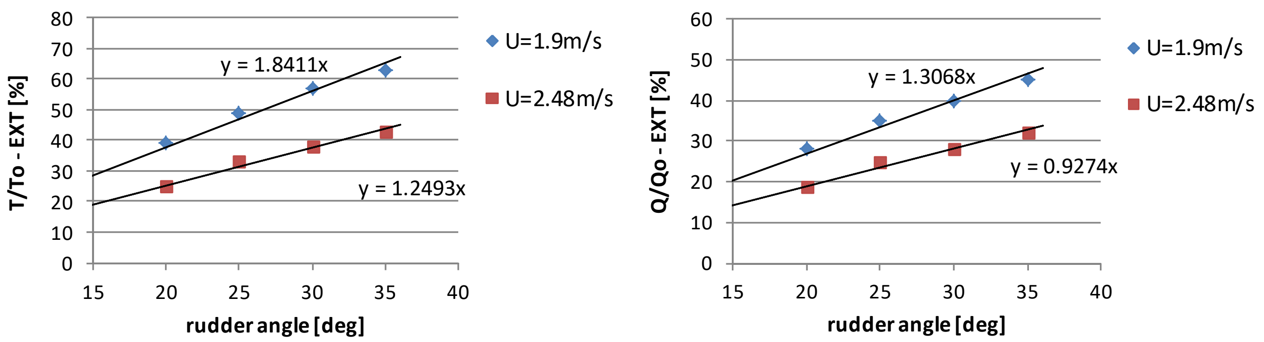

Figure 14 Derivative overload slopes of propeller thrust and torque at turning maneuvers.

Based on the developed experimental approach, the coefficients $q_T^{p,s\,'}$ and $q_Q^{p,s\,'}$ are formulated, which can evaluate the asymmetric efficiency of the hydrodynamic characteristics of a twin screw, respective to thrust and torque in curvilinear maneuvers.

The critically external torque overload values are above 40 % and are at rudder angles above 30°. The speed, accordingly, is Froude number Fn = 0.34. Nevertheless, **Figure 14** shows an interesting tendency- at the higher speed, which is Fn = 0.44, the higher external torque overload is almost equal to the lowest overload at Fn = 0.34. Based on these investigations and others (Coraddu et al., 2013; Dubbioso & Viviani, 2012b), it is possible to determine the critical maneuvering mode-above Fn = 0.3 at rudder angle 30°, which matches to $q_Q^{p,s'} > 1$;

For better understanding of the phenomenon and clear determination of the critical maneuvering modes and the limits of $q_T^{p,s'}$ and $q_Q^{p,s'}$, detailed test matrices consisting of variations of the distance between the units of twin screw systems, turning circle maneuvers, and Froude numbers should be planned.

References

ANEP-70 Volume I. (2003). *Guidance for naval surface ships mission oriented manoeuvring requirements*. NATO Allied Naval Engineering Publication 70.

Basin, A. M. (1977). *Propulsion and handling of ships* (in Russian). Moscow, Transport.

Coraddu, A., Dubbioso, G., Mauro, S., & Viviani, M. (2013). Analysis of twin screw ships asymmetric propeller behaviour by means of free running model tests. *Ocean Engineering, 68*, 47-64. doi:10.1016/j.oceaneng.2013.04.013

Dubbioso, G., & Viviani, M. (2012a). Aspects of twin screw ships semi-empirical manoeuvring models. *Ocean Engineering, 48*, 69-80. doi:10.1016/j.oceaneng.2012.03.007

Dubbioso, G., & Viviani, M. (2012b). *Experimental investigation of asymmetrical propeller behaviour of twin screw ships during manoeuvres*. In Proceedings of the International Conference on Marine Simulation and Ship Maneuverability 2012. Singapore.

Dubbioso, G., Mauro, S., & Viviani, M. (2011). *Off-design propulsion power plant investigations by means of free running manoeuvring ship model test and simulation techniques*. In Proceedings of the 21st International Offshore and Polar Engineering Conference. Hawaii, USA.

Efremov, D. (2015). *Simulation model of the "Main Engine-Hull-Propeller" system dynamics in ship manoeuvring motion* (in Bulgarian). Ph.D. Thesis, Bulgarian Ship Hydrodynamics Centre, Bulgarian Academy of Sciences.

Efremov, D. (2016). Experimental investigation of asymmetric behavior of propeller shafts during maneuvering of twin screw ship. *Engineering Sciences, 63*, 63-77.

Efremov, D., & Milanov, E. (2017). Investigation of twin-rudder load asymmetric behaviour by free-running model tests. In Proceedings of the 21st International Conference on Hydrodynamics in Ship Design and Operation. Gdansk, Poland.

Fedyaevsky, K. K., & Sobolev, V. G. (1963). *Ship handling* (in Russian), Sudpromgiz.

Fossen, T. I. (2005). A nonlinear unified state-space model for ship maneuvering and control in a seaway. *International Journal of Bifurcation and Chaos, 15*(9), 2717-2746. doi:10.1142/S0218127405013691

Goffman, A. D. (1988). *Propulsion and steering complex and manoeuvring the vessel* (in Russian). Shipbuilding, Leningrad.

Goodman, A., Gertler, M., & Kohl, R. (1976). *Experimental techniques and methods of analysis used at hydronautics for surface: Ship maneuvering prediction*. In Proceedings of the 11th Symposium on Naval Hydrodynamics. London.

Gutshe, F. (1964). *Untersuchungen Schiffsschrauben in schräger Ausstromung* (in Russian), Schiffbauforschung.

Khanfir, S., Hasegawa, K., Kobayashi, E., & Nagarajan, V. (2012). *Mathematical model for manoeuvring of twin-propeller twin-rudder ship considering peculiar rudder normal force phenomenon*. In Proceedings of the International Conference on Marine Simulation and Ship Maneuverability 2012. Singapore.

Molland, A. F., & Turnock, S. R. (2007). *Marine rudders and control surfaces*. Elsevier, London, UK. doi:10.1016/B978-0-7506-6944-3.X5000-8

Ortolani, F., Viviani, M., Tani, G., & Dubbioso, G. (2020). Experimental investigation of single blade loads by captive model tests in pure oblique flow. *Ocean Engineering, 196*, 106789. doi:10.1016/j.oceaneng.2019.106789

Vasiliev, A. V. (1989). *Ship handling* (in Russian). Shipbuilding, Leningrad.

Viviani, M., Bonvino, C., Mauro, S., Cerruti, M., Guadalupi, D., & Menna, A. (2007). *Analysis of asymmetrical shaft power increase during tight manoeuvres*. In Proceedings of the 9th International Conference on Fast Sea Transportation. Shanghai, China.

Voitkunsky, Y. I., Faddeev Y. I., & Fedyaevsky, K. K. (1982). *Hydromechanics* (in Russian). Shipbuilding, Leningrad.