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Hydrodynamic characteristics of the propulsion thrusters of an unmanned ship model

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Abstract

In this paper, an experimental model has been developed to study an unmanned ship. Two aft azimuthal propellers and two bow tunnel thrusters were used to propel the ship. In order to develop algorithms and a computer program to control the model, it is necessary to determine the hydrodynamic characteristics of the propellers installed in the model. The propellers are very small; therefore it is impossible to use approximate methods of calculating the thrust of the ship's propellers. The characteristics of the thrust of the propellers installed in the model were measured experimentally. This paper has given a description of the test stand and the results of the measurement of the thrust forces of the propellers installed in the model of an unmanned ship.

Introduction

The commencement of research, design and construction of prototypes of unmanned ships, ultimately controlled autonomously, requires the development of algorithms and specialized software to control them. The installation of an onboard computer with control software on an unmanned ship will require a lot of research and tests to be carried out on the operational accuracy of the autonomous system. However, before the control software can be installed onboard the vessel, tests of the control software should be carried out on a land-based computer simulation.

In the computer simulation software, one of the basic modules is a mathematical model of the propulsion system from which the power and thrust forces of the individual propellers are calculated, with simultaneous optimization of these values for the set parameters of the movement of the unmanned ship.

The currently realized research, as well as the planned further simulation research and experimental research, were conducted on physical models of unmanned ships. Therefore, it is necessary to investigate the hydrodynamic characteristics of the propellers installed in the models of the unmanned ships.

There are publications in the literature that can be used to calculate the hydrodynamic characteristics of the propellers of a typical ship (Eckhardt & Morgan, 1955; Lammeren, Manen & Oosterveld, 1969; Oosterveld, 1969; Oosterveld & Oossanen, 1975); however, these parametric methods were developed for propellers on large ships.

There are also results of model tests of screws in cavitation tunnels in the literature (Jarzyna, Koronowicz & Szantyr, 1996); however, these screws have diameters that are too large to be used on small experimental models of unmanned ships. Azimuthal and tunnel thrusters are planned for use for propulsion and control on the designed unmanned ships. Therefore, in experimental models of the unmanned ships, such propellers will also be used. However, there are no precise methods for calculating the hydrodynamic characteristics of such small diameter propellers.

In order to determine the characteristics of small diameter propellers, basin model tests (Pena et. al., 2013; Zondervan, Grasso & Lafeber, 2017) and numerical CFD calculations (Bugalski & Hoffmann, 2011; Tabaczek & Bugalski, 2014; Berchiche, Krasilnikov & Koushan, 2018) have been performed.

As it is not possible to use approximate methods for calculating the hydrodynamic characteristics of ship propellers or model test results for screws of given dimensions, for the designed model of an unmanned ship, the measurements of the propellers' characteristics should be carried out on the experimental stand.

Objective of the research

When used in an experimental model of an unmanned ship, the propulsion system, as on the actual vessel, should perform all of the following manoeuvres:

- sailing out of port after the ship has been loaded;
- voyage to the destination port after an optimal shipping route;
- collision avoidance manoeuvres (avoidance of fixed and moving obstacles – other ships or floating objects);
- entry manoeuvres to the destination port and berthing.

The purpose of the research is to design the propulsion system of an unmanned ship, which will perform all of the aforementioned manoeuvres and to experiment with the hydrodynamic characteristics of the propellers.

Propulsion system of the experimental model of an unmanned ship

In 2018 a design of an unmanned container ship (bulk carrier), which was autonomously controlled, was produced, Figure 1. A 1:25 scale model of an unmanned ship, as shown in Figure 2, was built to test the control system and the propulsion system.

The experimental model of the unmanned ship was equipped with an ecological propulsion system of the same design as that intended for use on a real unmanned ship. The propulsion system (Figures 2 and 3) consisted of:

- 2 stern azimuthal propellers (APL and APR) powered by electric motors,
- 2 bow tunnel thrusters (BT1 and BT2) powered by electric motors.

Each electric motor had its own power supply (batteries) and its own controller to control the rotational speed of the propellers.

The propulsion control system of the model was constructed in such a way that it is possible to:

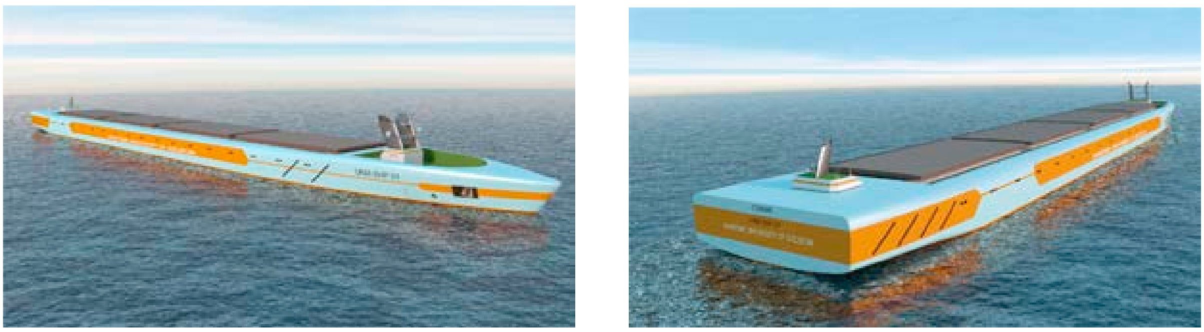

Figure 1. Visualisation of the design of an unmanned, autonomously controlled, container ship (bulk carrier) (L_C = 78.75 m, B = 11.10 m, T = 4.33 m, ∇ = 2500 m^3)

Figure 2. The propulsion system of the autonomous ship model

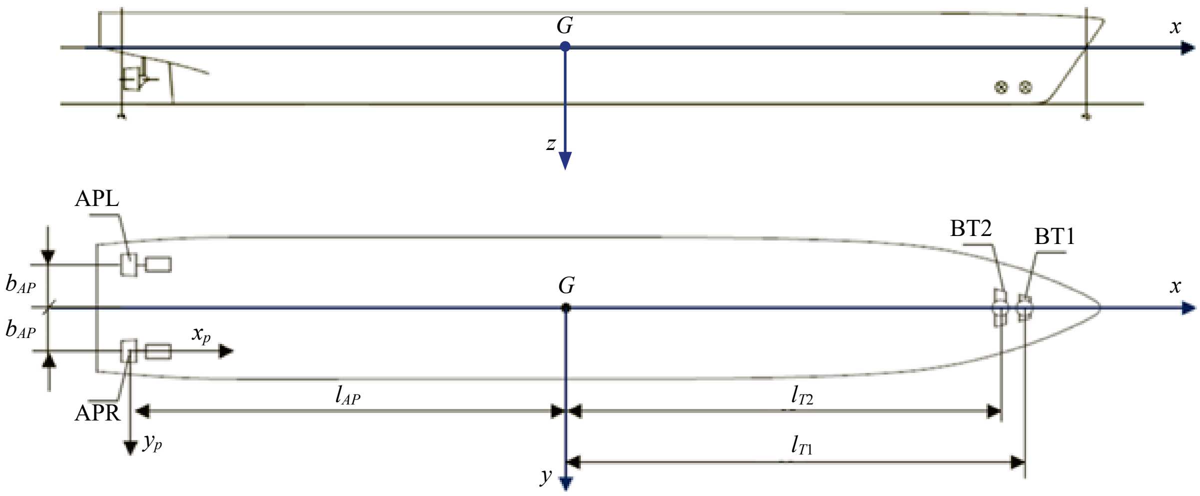

Figure 3. Position of the propellers in the propulsion system of the autonomous vessel model

- control each propeller individually,
- control the entire drive system by directing the resultant thrust force in any direction.

The ship could be controlled:

- by wireless remote control,
- autonomously – the model was controlled by the on-board computer with appropriate software.

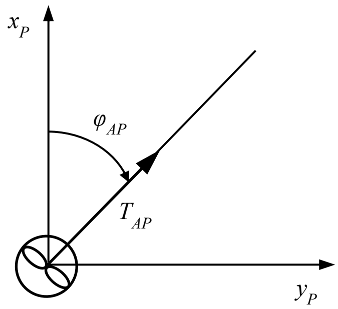

Figure 4. Angle of the azimuthal thruster setting

Generalised forces acting on the propellers of the propulsion system of the ship's model

The different functions of a voyage of the model or a real unmanned ship will require the thrust and moment components of the *Gxyz* system to be calculated, relative to the centre of mass of the vessel (Figure 3), for the propellers of the propulsion system.

For the stern (Figure 3) azimuthal propellers, the components of the resultant thrust force and moment about the *z*-axis are as follows:

$$\begin{aligned} R_{xAP} &= T_{APL}\cos\varphi_{APL} + T_{APR}\cos\varphi_{APR} \\ R_{yAP} &= T_{APL}\sin\varphi_{APL} + T_{APR}\sin\varphi_{APR} \\ M_{zAP} &= T_{APL}(\cos\varphi_{APR} b_{AP} - \sin\varphi_{APL} l_{AP}) + \\ &\quad - T_{APR}(\cos\varphi_{APR} b_{AP} + \sin\varphi_{APR} l_{AP}) \end{aligned} \tag{1}$$

where:

T_{APL}, T_{APR} – the thrust of the left and right azimuthal propellers;

φ_{APL}, φ_{APR} – angle of the azimuthal propellers: left and right (in the arrangement connected with the vertical axis of the propeller, Figure 4, parallel to *Gxyz*);

l_{AP} – the distance between the propellers and the centre of mass of the ship's model (Figure 3).

The components of the resultant thrust force and the moment about the *z*-axis of the tunnel bow thrusters (Figure 3) are as follows:

$$\begin{aligned} R_{xBT} &= 0 \\ R_{yBT} &= T_{BT1} + T_{BT2} \\ M_{zBT} &= T_{BT1} l_{T1} + T_{BT2} l_{T2} \end{aligned} \tag{2}$$

where:

T_{BT1}, T_{BT2} – thrust of tunnel thrusters 1 and 2,

l_{T1}, l_{T2} – coordinates of the position of tunnel thrusters No. 1 and 2 from the centre of mass of the model ship (Figure 3).

In both systems of equations (1) and (2), there are the thrust forces of the propellers, T_{AP} and T_{BT} respectively, which are the unknown hydrodynamic characteristics of these propellers.

In the azimuthal propellers and the bow thrusters that are used for the propulsion system of the ship model (Figures 2, 3), the thrust force is regulated by the change of the propeller's rotational speed. The value of the thrust force for the azimuthal propellers also depends on the angle of the propeller's position in relation to its vertical axis (at certain positions of the propeller – its rotation in relation to its vertical axis – a decrease in the thrust may occur due to interaction with the model's hull, as well as the screw propeller's stream from the opposite side).

Hence, the thrust of the azimuthal propeller can be determined as follows:

$$T_{AP} = f\,(G_P,\ n_P,\ \varphi_{AP},\ c_P) \tag{3}$$

where:

G_P – the geometric parameters of the propeller,
n_P – propeller speed,
c_P – correction factor, taking into account the drop in the thrust from the influence of the model's hull and the adjacent propeller,

For the bow thrusters, the thrust of the propeller can be determined by the following:

$$T_{BT} = f\,(A_T,\ n_T,\ C_T) \tag{4}$$

where:

A_T – geometrical parameters of the tunnel thrusters,
n_T – speed of the thruster screw,
C_T – correction factor for the length of the tunnel, shape of the hull opening, speed of the ship model.

There are no simple methods for calculating the hydrodynamic characteristics of such small ship's propellers in the literature. There are also no results of model tests in a cavitation tunnel that could be used to calculate the hydrodynamic characteristics of the propellers used on the unmanned ship model shown in Figure 2.

Therefore, the aim of this research was to experimentally determine the hydrodynamic characteristics of the stern azimuthal propellers $T_{AP} = f\,(G_P,\ n_P,\ \varphi_{AP},\ c_P)$, (3) and the bow tunnel thrusters $T_{BT} = f\,(A_T,\ n_T,\ C_T)$, (4).

Experimental method

The control system for any of the propellers of the autonomous ship model (Figure 3) is shown in Figure 5.

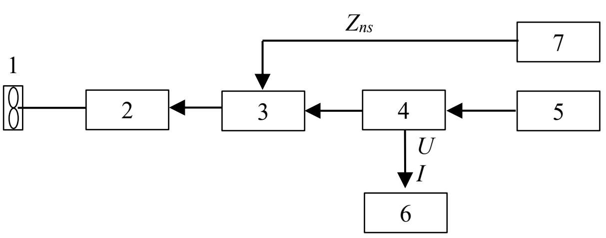

Figure 5. The control system of the model vessel's propeller; 1 – propeller, 2 – electric motor, 3 – motor controller, 4 – power measurement module (*U* voltage and *I* current measurement), 5 – battery, 6 – motor parameter recorder, 7 – motor speed control system Z_{ns} (vessel's remote control receiver or on-board computer for autonomous control)

The propellers of the propulsion system of the ship model do not have adjustable pitch, and there is no ability to measure the speed of the propeller's motor. Although for DC brushless motors there is an equation that can be used to calculate the rotational speed:

$$n_S = U \cdot KV \tag{5}$$

where:

n_S – speed of the brushless DC motor,
U – voltage of the motor's power supply,
KV – parameter for the particular motor type.

The equation (5) is then true for idle running (it is not true under load, even though the controller is able to maintain a constant speed).

The measurements for the hydrodynamic characteristics of the propellers used in the model of the unmanned ship were carried out in the following form:

- for the aft azimuthal thrusters:

$$T_{AP} = f\,(P_{AP},\ \varphi_{AP}) \tag{6}$$

- for the bow tunnel thrusters:

$$T_{AP} = f\,(P_{BT}) \tag{7}$$

where:

P_{AP} – power delivered to the motors of the azimuthal propellers (resulting from the measurement of the voltage U and the current intensity I),
P_{BT} – power delivery to the motor of the tunnel thrusters.

The speed control (and thus the thrust control) is performed using the Z_{ns} parameter. The relationship between the power of P_{AP} or P_{BT}, and the value of the Z_{ns} control signal sent by the system, 7, could then be determined (Figure 5).

The measurements of the hydrodynamic characteristics of the propellers, in the form of equations (6) and (7), when installed in the model of the unmanned ship (Figures 2, 3), were carried out in the model basin using electronic dynamometers (force meters) – Figure 6.

Electronic dynamometers, used for force measurements, were mounted as shown in Figure 6 (the coordinates of the fixing points and the initial position of the model in relation to the basin were known quantities).

The difference between the initial skid in the $G_0x_0y_0$ system and the position during the measurements in the Gxy system was taken into account when calculating the thrust T_{AP} and T_{BT} from the dynamometer readings.

In the course of the research, the following were simultaneously recorded in real time:

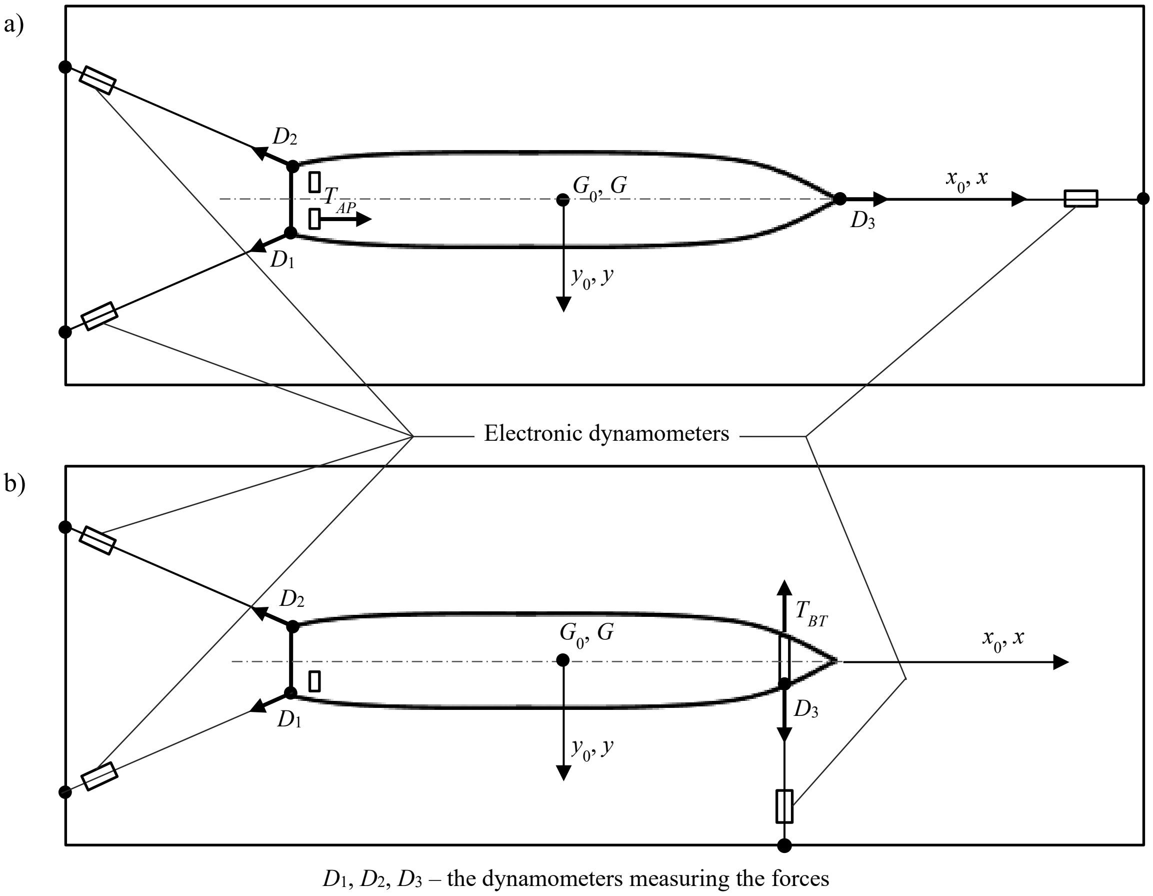

Figure 6. Measurement of the hydrodynamic characteristics of the stern (a) and bow (b) propellers in the model pool (the electronic dynamometers had a measurement range from 0 to 20 N with an accuracy of 0.05 N)

- dynamometer readings D_1, D_2, D_3;
- power supply voltage U and current I to the propulsion motors (power measurement module, Fig. 5);
- for the azimuthal propellers, the angle φ_{AP} of the propellers' settings were measured (Fig. 4);
- the value of the signal controlling the preset speed of the drive motors (system 7, Fig. 5).

The dynamometers, D_1, D_2 and D_3, were directly connected to the computer to record their values. The recorded voltage U and current I, as well as the value of the speed control signal of the drive motor, were transmitted to the measuring computer via radio using a telemetry system.

On the basis of the measurements from the dynamometers, D_1, D_2 and D_3, and from the three equations recorded in the *Gxy* system, the thrust forces generated by the propellers of the ship model could be calculated.

Results

The values of the measured thrust of the propellers installed in the ship model have been shown in Table 1 and Figures 7 and 8.

Table 1. Results of the measurement of the thrust forces of the propellers

Azimuthal thruster			
Angle of thruster setting φ_{AP} = 0°			
Voltage U_{AP} [V]	Current I_{AP} [A]	Power P_{AP} [W]	Thrust T_{AP} [N]
22.65	1.1	24.9	5.7
22.57	2.0	45.1	8.5
22.44	3.6	80.8	11.0
22.27	6.3	140.3	14.5
22.15	7.6	168.3	15.2
Angle of thruster setting φ_{AP} = 45°			
20.75	2.8	16.6	6.2
22.59	1.1	24.8	7.4
22.50	1.3	29.6	7.8
22.38	3.0	67.1	11.4
22.20	4.4	97.7	12.0
Tunnel thruster			
Voltage U_{BT} [V]	Current I_{BT} [A]	Power P_{BT} [W]	Thrust T_{BT} [N]
12.11	0.64	7.7	1.0
12.03	0.87	10.5	1.3
11.90	1.32	15.7	1.9
11.80	1.53	18.1	2.0
11.73	1.78	20.9	2.2
11.67	1.98	23.1	2.4
11.56	2.20	25.4	2.6

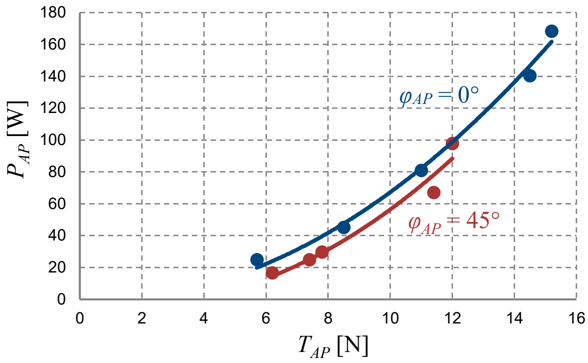

Figure 7. Characteristics of the azimuthal propeller

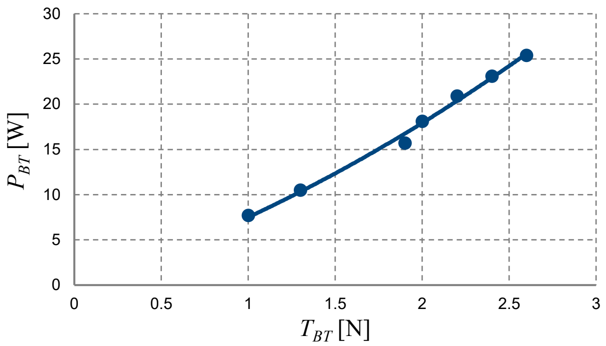

Figure 8. Characteristics of the tunnel thruster

Conclusions

1. The measuring system that has been presented in this article can be used for sufficiently accurate measurements of the thrust forces of the propulsors installed in the ship model, depending on the power of the propulsion motors.
2. The obtained propeller thrust characteristics (Figures 7 and 8 and Table 1) are only correct for the propellers installed in the ship model.
3. The measured thrust characteristics are correct for the bollard pull test performed on the ship model – lack of speed V of the ship.
4. For the azimuthal propellers there was a small drop in the thrust, depending on their setting angle (angle φ_{AP}, Figure 4).
5. The resulting characteristics will be used to measure the thrust while the model is moving at speed V. In the authors' further research, the sensors installed in the ship model will measure the current speed of the model in real time, while also measuring the power supplied to the propulsion motors. In order to determine the thrust characteristics of the propellers of the ship model at certain speeds, the model's resistance characteristics at different speeds will be determined (the resistance calculations will be performed using the CFD method).

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