Analysis of Efficiency of Full-submerged Archimedes Screws of Rotary-screw Propulsion Units of Snow and Swamp-going Amphibious Vehicles

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Abstract: The paper presents results of the numerical analysis of propulsive characteristics of full-submerged Archimedes screws of rotary-screw propulsion units of snow and swamp-going amphibious vehicles with the most typical geometric characteristics for this class of vehicles. The received performance curves and the pictures of visualization of interaction between water environment and Archimedes screws with different helix angles are given. The maximum available values of efficiency determinants of Archimedes screws for cruising and mooring modes are determined. The results of comparative analysis of efficiency of Archimedes screws and propellers with the same operation conditions are considered. The ways to increase the efficiency of rotary-screw propulsion units of snow and swamp-going amphibious vehicles according to the results received are designated. The results and the conclusions obtained as part of the study could be used by developers of amphibian with rotary-screw propulsion units to estimate and provide the overwater characteristics.

1 INTRODUCTION

The traditional designing of water propulsion units in shipbuilding intends the realization of specific procedure, the main part of which is to determine the geometrical parameters of the working body of water propulsor with the help of performance curves of systematical series based on results of tests in hydrodynamic laboratories. For example, when designing the amphibia moving afloat by the medium of propellers the performance curves of public Troost or Kaplan series got by shipbuilders are usually used. The developers of amphibian vehicles with rotary-screw propulsion units (RSP) haven't got such possibility. This is due to the mild interest of shipbuilders in rotary-screw propulsors (because of their low propulsive characteristics in comparison with propellers) and the lack of attention of developers and researches of amphibian with RSP to vehicle overwater characteristics. Among the last one it is definitely necessary to point the experimental works of Cole (1961) and theoretical studies of Sogin and Shapkin (2006); however, they did not conduct full systematic studies of the RSP hydrodynamics.

2 COMPUTER SIMULATION OF PROPELLER

To get the full relevant view of afloat performance of the rotary-screw propulsor it is essential to perform the enough amount of physical or simulation

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experiments with different input parameters and wide range of values of them, meanwhile the results of computer simulation demand the verification more than other one. Further it is planned to create the stand to get the verification data based on the results of physical model tests of Archimedes screws, but at this stage of research it was decided to use computer simulation for preliminary estimation. To estimate the adequacy and accuracy of the results obtained it would be a good idea to compare them with the data of Cole research but he used too small physical model in his experiments which always leads to inevitable impact of scale effects, moreover, the water tests were performed in mooring mode only, and the small dimensions of test basin relatively to the model of Archimedes screw led to presence of reverse flows which skewed the results of experiment (Shapkin, 2017). Cause of this the computer model was processed and tested on Troost series propeller with close topology and similar performance conditions (Figure 1).

For verification the five-blade propeller with maximum disk-area ratio of series was selected to provide the adequate comparison. Such selection is defined by the specificity of design of rotary-screw propulsion unit which has rather high disk-area ratio, in other words, the ratio of an expanded area F_{bl} of all elements of blade system to area of circle with diameter equal to propeller diameter:

$$\theta = \frac{4z \cdot F_{bl}}{\pi \cdot D^2} \tag{1}$$

Propeller parameters are given in the Table 1. Here pitch ratio is the ratio of propeller pitch – the distance traveled by propeller in one full revolution in translational direction – to propeller diameter; hub ratio is the ratio of hub diameter to propeller diameter (Basin, 1977).

Figure 2 shows performance curves conforming to the propeller selected (Bernitsas, 1981). The diagrams show the correspondences of non-dimensional coefficients built in relative coordinates.

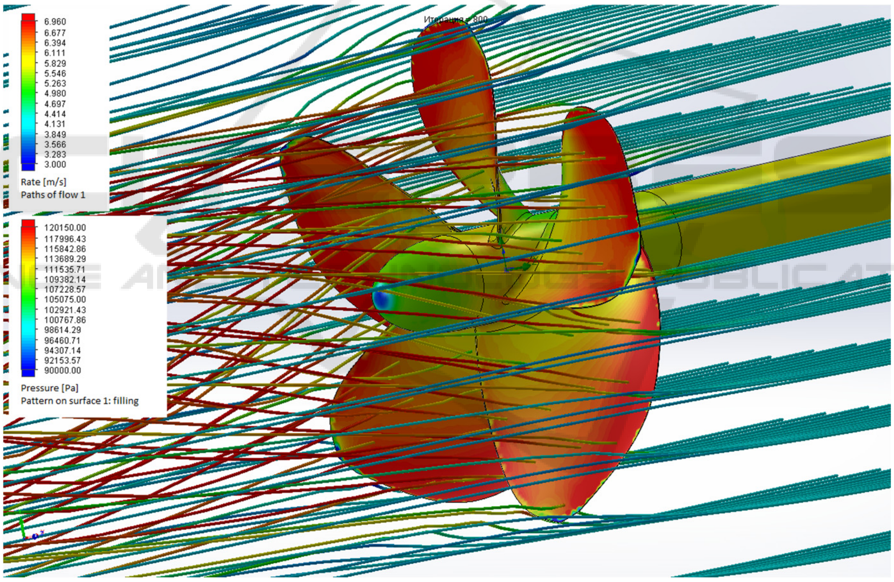


Figure 1: Propeller B 5.105.1.4 (the visualization pattern of computer simulation: v=4 m/sec, n=500 rpm).

Table 1: Propeller parameters.

Parameter	Designation	Value
Diameter, mm	D	800
Blade number, pcs	z	5
Pitch ratio	H/D	1.4
Hub ratio	d/D	0.325
Disk-area ratio	θ	1.05

Thrust coefficient:

$$K_T = \frac{T}{\rho \cdot n^2 \cdot D^4} \quad (2)$$

Torque coefficient:

$$K_Q = \frac{Q}{\rho \cdot n^2 \cdot D^5} \quad (3)$$

Propulsive coefficient (efficiency):

$$\eta_0 = \frac{J}{2\pi} \cdot \frac{K_T}{K_Q} \quad (4)$$

Advance ratio:

$$J = \frac{v_a}{n \cdot D} \quad (5)$$

In the above formulas $\rho = 1000\ kg/m^3$ is water density, T is propeller thrust (N), Q is torque of propeller shaft (N•m), n is propeller rotational speed (rpm) and v_a is speed of water flow (m/sec).

Performance curves essentially characterize the performance of the particular propeller moving with the particular rotation speed. For all geometrically similar propellers their hydrodynamical characteristics shown in such correspondences are identical. The advance ratio characterizing the performance mode uniquely determines thrust and torque coefficients. The correspondence of propulsive coefficient becomes equal to zero in two end points: in the first instance there is no speed, in the second – no thrust; the function runs up to extremum with specific correlation of all data which forms the range of recommended values of parameters for even particular propeller (https://studwood.ru, 2022/01/17).

As a result of computer simulation there were procured the correspondences of thrust and torque of propeller in open water when the flow speed is 4 m/sec in the range of rotation speed from 200 to 600 rpm. The diagrams (figure 3) show that the maximum divergence of values of thrust and torque got during physical and computer modelling is not more than 5 and 2 percent respectively. Such inaccuracy is thoroughly acceptable for comparative analysis.

3 COMPUTER SIMULATION OF ROTARY-SCREW PROPULSION UNITS

Parameters of RSP modelled were determined according to the results of analysis of existing snow and swamp-going amphibious vehicles (Kolotilin, 2015; Danilov, 2011; Kulyashov and Kolotilin, 1993; Nikolaev and Kulyashov, 1973).

The comparative estimation of geometrical parameters showed that their values for the most part of amphibian are in the particular ranges (table 2). One of the main factors determining the dynamical characteristics of RSP in afloat motion is the helix angle of Archimedes screw φ. This parameter essentially effects on thrust and torque of propulsor

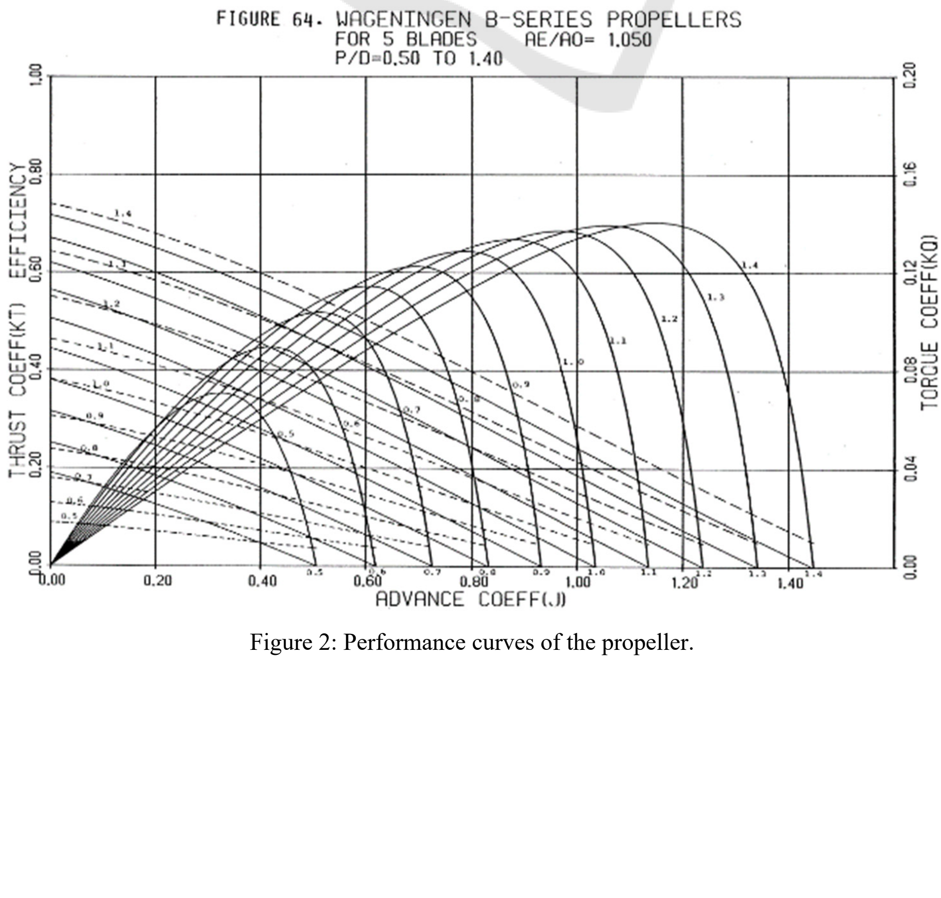
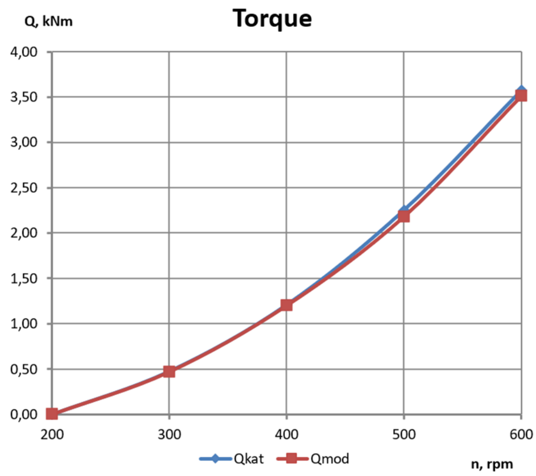
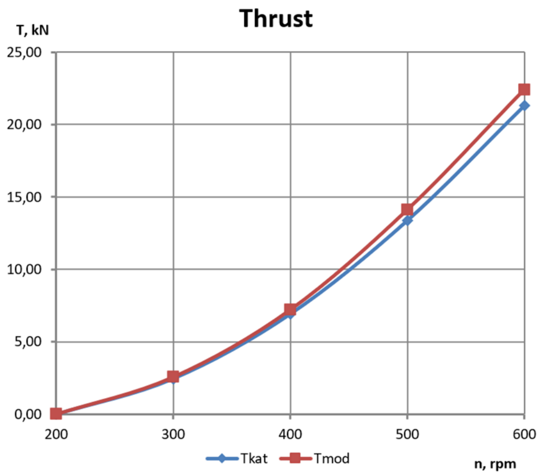


Figure 2: Performance curves of the propeller.



a) Propeller torque



b) Propeller thrust

Figure 3: Comparison of the results of computer simulation and the results of model testing of propeller in test basin.

Table 2: Value ranges of geometrical parameters of RSP.

Parameter	Designation	Value
Diameter, mm	D	600...1000
Blade number, pcs	z	1...3
Pitch ratio	H/D	1.46...2.83
Hub ratio	d/D	0.7...0.9
Disk-area ratio	θ	1.2...2.5
Helix angle, °	φ	24...42

Table 3: Geometrical parameters of Archimedes screw models researched.

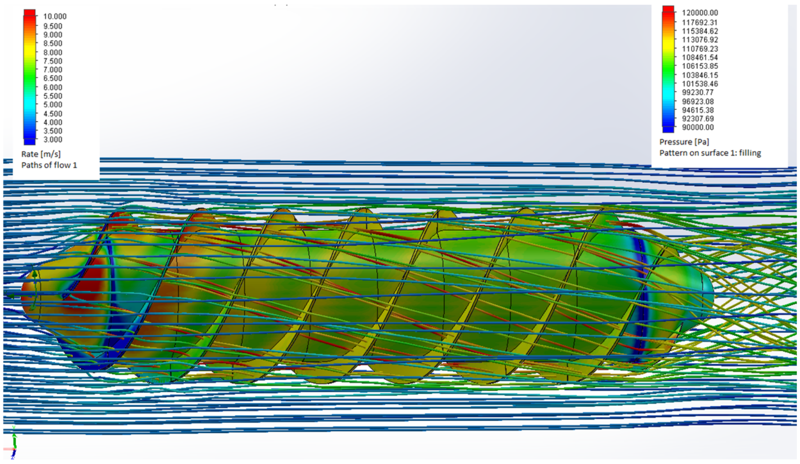
Parameter	Model №1	Model №2	Model №3
D	800	800	800
z	3	3	3
H/D	1.4	1.8	2.5
d/D	0.8	0.8	0.8
θ	3.48	2.91	2.35
φ	24	30	39

and when the angular speed is permanent these characteristics grow while angle φ increases. For the preliminary estimation of RSP efficiency in afloat motion in full-submerged mode three models with end and middle values of angle φ were created (table 3).

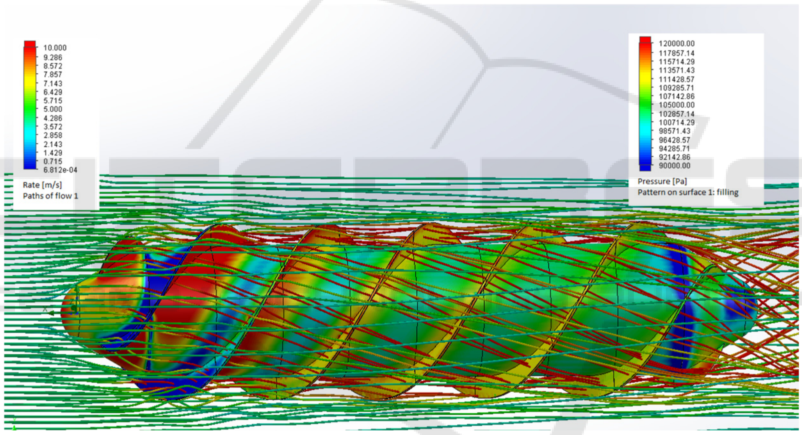
Besides the evident, geometrical, parameters impacting on the hydrodynamical characteristics of propulsor the other factors should be noted, specifically the performance peculiarities of rotary-screw propulsion units of snow and swamp-going amphibious vehicles in afloat motion essentially determining the efficiency of RSP water moving (Karaseva, 2021). These include the performance of Archimedes screws of the most part of amphibian in semi-submerged mode, the interaction between RSP Archimedes screws and amphibia hull and the joint action of Archimedes screws of amphibious vehicles with tandem RSP as the most widespread design. At this stage the aim was to simulate the performance of single RSP apart from the vehicle in full-submerged mode; however, in further research for development of the calculation procedure of optimal parameters of rotary-screw propulsion units while afloat performance it is necessary to take into account all factors.

Computer simulation for variations of Archimedes screw design considered was done for travelling mode ($v = 4\ m/sec$, $n = 200 \ldots 1000\ rpm$) and mooring mode ($n = 200 \ldots 600\ rpm$).

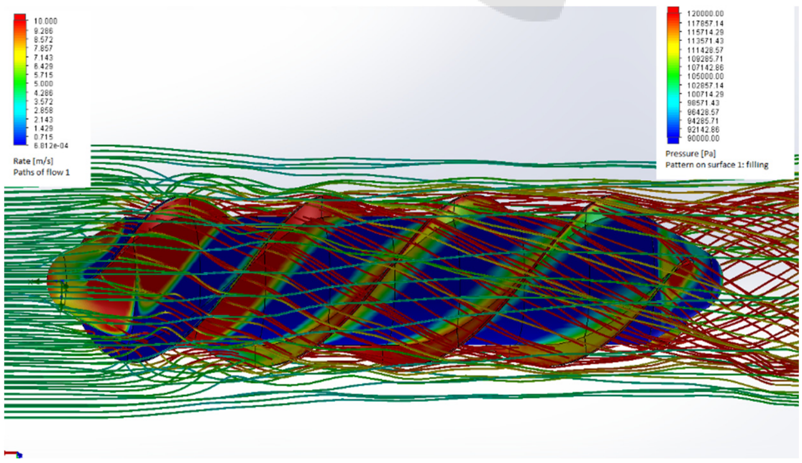
As a result, the large data set was got. Some visualization patterns of the computer simulation results are shown in the Figure 4.



a) Helix angle φ=24°



b) Helix angle φ=30°



c) Helix angle φ=39°

Figure 4: Visualization patterns of computer simulation of hydrodynamics of full-submerged Archimedes screw of RSP (v=4 m/sec, n=500 rpm).

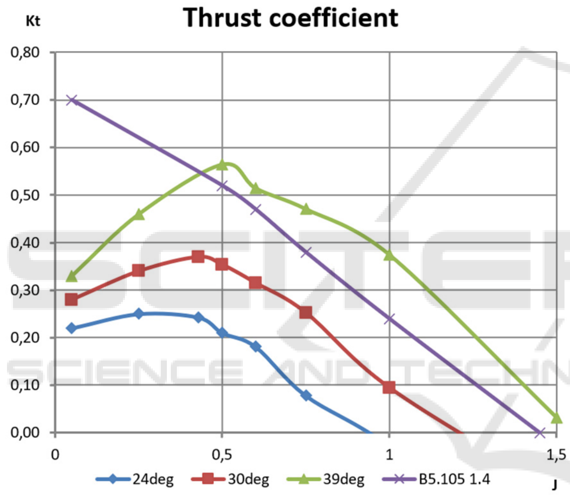
4 COMPARATIVE ANALYSIS

Figure 5 gives the performance curves of three variations of rotary-screw propulsors and of propeller of Troost series in relative coordinates got as a result of computer simulation. The analysis of curves received shows that in travelling mode in the range of values of advance ratio simulated Archimedes screws with geometrical parameters peculiar to RSP of snow and swamp-going amphibian have the maximum efficiency values range from 0.16 to 0.22 growing while increasing of helix pitch (increasing of helix angle φ). In the mooring mode the efficiency of using of input power is usually characterized by relative quality coefficient (Vasil'ev, 2006)

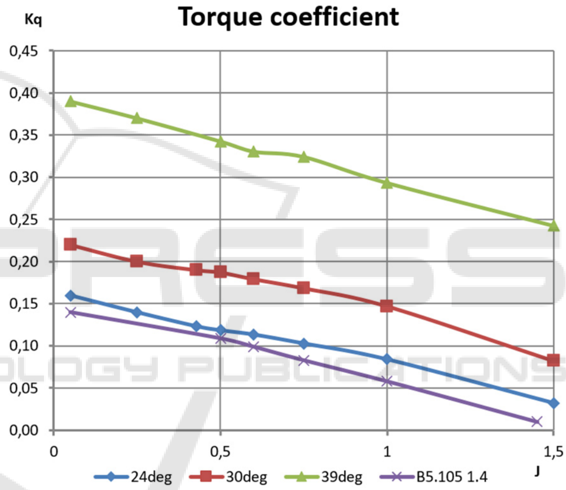
$$\xi' = \frac{T}{1{,}16(ND)^{2/3}} \qquad (6)$$

Here N is shaft power (kW), and ξ' lies in the range 0.31…0.38. The model with helix angle 30 degrees has the maximum efficiency in all range of rotational speeds.

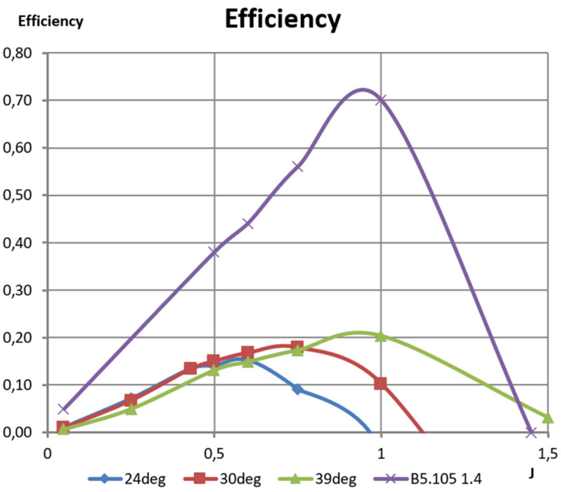
Therefore, the limiting efficiency of Archimedes screws is essentially inferior to the same of propellers in open water; efficiency of the last ones in the range covered can reach 0.7 and relative quality coefficient lies in the range 0.86…0.98. Comparably low efficiency of Archimedes screws is determined foremost by the presence of massive hub which resistance is essentially grows with increase of both movement speed and rotation speed. One more factor reducing efficiency is the nonuniformity of the distribution of thrust forces along the helixes of Archimedes screws graphically illustrated by the patterns of dynamical pressures shown in the Figure 4.



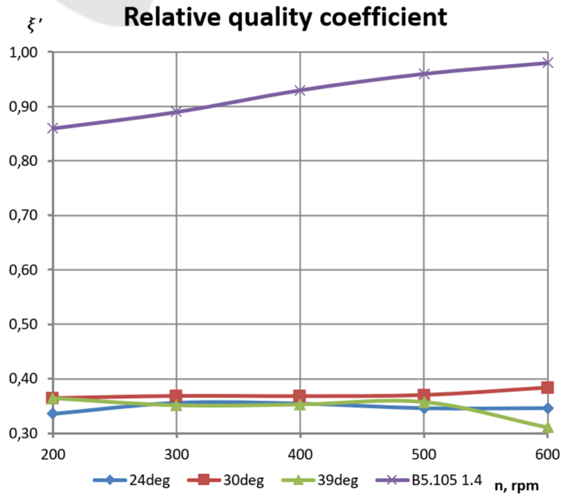
a) Thrust coefficient



b) Torque coefficient



c) Efficiency



d) Relative quality coefficient

Figure 5: Characteristics of propeller and rotary-screw propulsion units.

When designing of rotary-screw propulsion units of snow and swamp-going amphibious vehicles it should be considered that:

1. The efficiency of using of input power for full-submerged Archimedes screws of RSP in mooring mode and in typical range of moving modes is one-third of that of propellers with the same diameter.
2. The maximum efficiency of RSP Archimedes screws in travelling modes realises in the advance ratio range 0.6…1.0 (the higher values conforming to better overwater characteristics correspond to larger helix angles). When advance ratio is less than 0.5 Archimedes screws have non-typical for propellers reduction of thrust coefficient because of increasing of resistance of massive hub during growing of induced velocities.
3. The area of induced velocities along the Archimedes screw (according to the result of analysis of visualization patterns) which are 10 and more percent greater than velocity of approaching flow has diameter equal to 1.1…1.2 diameters of Archimedes screw. To reduce negative effects of interaction between Archimedes screw and amphibia hull it is necessary to locate Archimedes screws of RSP at the appropriate distance from the hull.

5 CONCLUSIONS

Archimedes screws of existent RSP perform in complex interaction with hull and appendages of amphibia and between each other, moreover, the semi-submerged mode is peculiar to snow and swamp-going amphibious vehicles. The aspects pointed require special research, nevertheless, the performance curves of Archimedes screws in open water received allow to determine the maximum speed of afloat motion in the early stages of designing when engine power and geometrical parameters of Archimedes screws are set by land performance conditions, and to correct these characteristics to improve overwater performance.

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