ENGINEERING AND MODELING OF OPTIMAL MANEUVERING OF VESSELS WITH VORTEX PROPULSION UNITS

Ostroukhov, Nikolai N., *Moscow Aviation Institute (National Research University) (MAI), Moscow, Russia.*
Chumakova, Ekaterina V., *Moscow Aviation Institute (National Research University) (MAI), Moscow, Russia.*

ABSTRACT

The paper proposes a schematic diagram of an additional device for vortex propulsion units of vessels and algorithms for computer simulation of their use for various maneuvering options.

The paper describes the advantages of vessels with propulsion units in the form of generators of vortex pairs, including toroidal vortices (thermals), the efficiency of propulsion units of which increases with the increase in their dimensions. A comprehensive analysis of the specifics of maneuvering of such vessels is presented. Practical inapplicability of traditional vessels' devices for changing the course of the vessel and unacceptable duration of reaching steady-state modes and the stopping process when using only regular vortex generators are shown.

A sequence of actions with vortex generators is described for the main types of maneuvers. In the paper, a schematic diagram of an additional device (with an estimation of its physical dimensions) is proposed to the vortex propulsion units of vessels, which ensures unwinding or braking of the «attached» mass for a predetermined time with minimal loss of power. Algorithms for computer simulation of the change in the nature of the flow in the closed flow region are developed using the proposed additional acceleration device. It is shown that the algorithms implemented in the work can be used in the control of a real vessel.

Keywords: water transport, water vessels and aircraft with vortex propulsion units, surface and underwater (toroidal) vessels, flow in the vicinity of the vortex pair, drag, steady and transient modes, attached mass of water, blade, rotor.

Background. *The development of the procedures of technical implementation of maneuvers of vessels with vortex propulsion units, including start of motion with the output to the steady-state mode, reverse process up to the stop of the vessel, change in the course from the conditions of pre-established time and minimal power consumed and principal non-use of traditional vessels' steering devices, as well as predesign of technical devices, which implement maneuvering.*

Advantages of vortex propulsion units [1–3] are implemented to the fullest extent in the steady-state mode of vessels' motion, i.e. at speed constant in value and direction. Such vessels are almost not subject to drag and power consumed by them is some orders lower than the same of vessels, made using a traditional scheme «body–propulsion unit», located one after another [4].

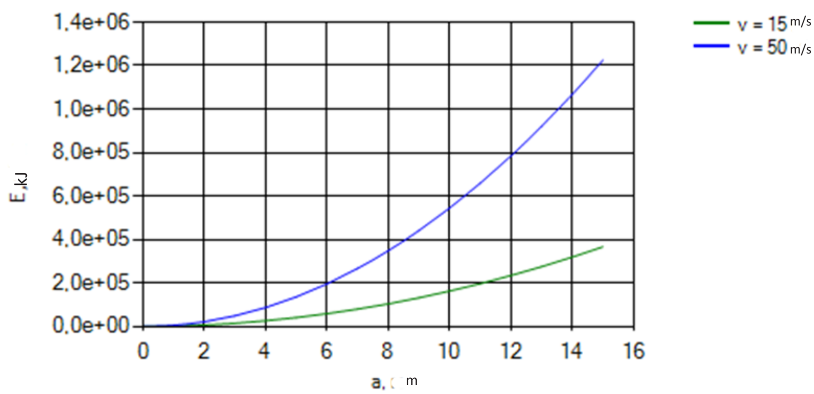
The nature of advantages of vessels described in [1], is that the propulsion unit does not «push» the vessel's body and itself through water or air, but being a generator of a vortex pair [4] and immersed in areas of closed flows in the vicinity of this pair, moves together with it.

The absence of drag is explained by the fact that in the entire space around the vortex pair the flow with continuous distribution of speed (without jumps) is realized [5–7]. The power to keep such flow and motion of vessels is due to the dissipative losses, i.e. for viscous friction on the surface (at the border) «vortex generator – medium». It should be noted that in surface vessels with vortex propulsion units the body is located above water and floatage of the vessel is ensured by the volume of vortex generators, immersed in water.

The rugged body of the submarine vessel is in the form of a hollow sealed torus, and its propulsion unit and vortex generator is a comparatively thin-walled toroidal shell, equidistant to the outer surface of the body and rotatable mounted relative to the body. Since the linear speed of the outer surfaces of the generators has cavitation limitations [1, 8], determined by the absolute pressure in the water environment, submarine vessels with vortex propellers can develop a speed much higher than the speed of the surface ones.

It is obvious that the mass of water (air in the case of an airship) in the closed flow region has kinetic energy

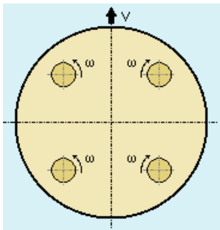
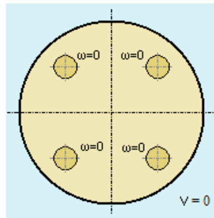
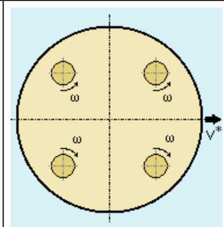
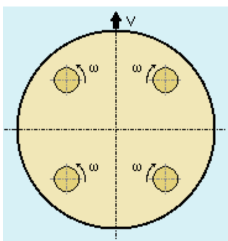
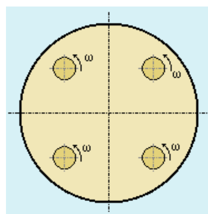
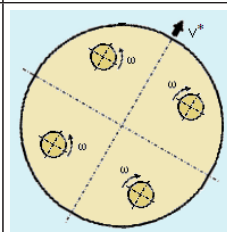
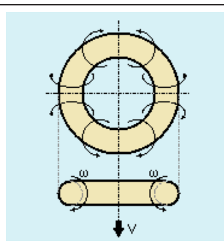
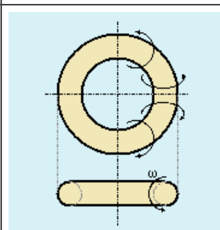
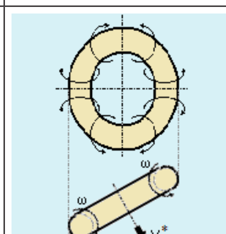
$$E = \frac{\rho}{2}\oint_{\Omega} v(r)^2 \, d\Omega, \quad (1)$$



Pic. 1. Dependence of the specific (per generator's linear meter) kinetic energy of the «attached» mass on the radius of the vortex generator.

Table 1

Summary table of change in rotation modes of vortex generators

Vessel's type			Initial mode	Transient mode	Steady-state mode (after maneuver)	Speed vector after maneuver
			a	b	c	
Surface vessel	Vessels' rotation and speed vector by angle $\pi/2$	I				$V^* = V\exp\left(i\frac{\pi}{2}\right)$
Surface vessel	Vessel's rotation and speed vector by angle φ	II				$V^* = V\exp(i\phi)$ $\phi = k\omega\tau$
Underwater vessel	Vessel's rotation and speed vector by angle φ	III				$V^* = V\exp(i\phi)$ $\phi = k\omega\tau$

where Ω – attached volume of water, i.e. volume of the closed flow region.

To estimate E it is possible to use

$E = D\nu^2$, *(1′)*

where D – displacement of the vessel (kg), ν – speed of its translational motion in the steady state.

Said kinetic energy is transmitted from the vortex generator to the attached mass during the entire time from the start of the drive propeller to the exit of the vessel to the steady state. The value of E can be very large, and the larger the size (displacement) of the ship, so that the vortex generator, designed only to compensate for the dissipative losses, can transmit this energy to the attached mass for a very large, possibly almost unacceptable, time [1].

From what has been said, it is clear that it is necessary to develop methods and devices for minimizing the time to reach the steady-state mode of vortex propulsors of vessels.

From what has been said, it is clear that it is necessary to develop methods and devices for minimizing the time to reach the steady-state mode of vortex propulsion units of vessels.

Objective. *The objective of the authors is to consider different aspects of engineering and modeling of optimal maneuvering of vessels with vortex propulsion units.*

Methods. *The authors use general scientific and engineering methods, modeling, comparative analysis, evaluation approach, scientific description.*

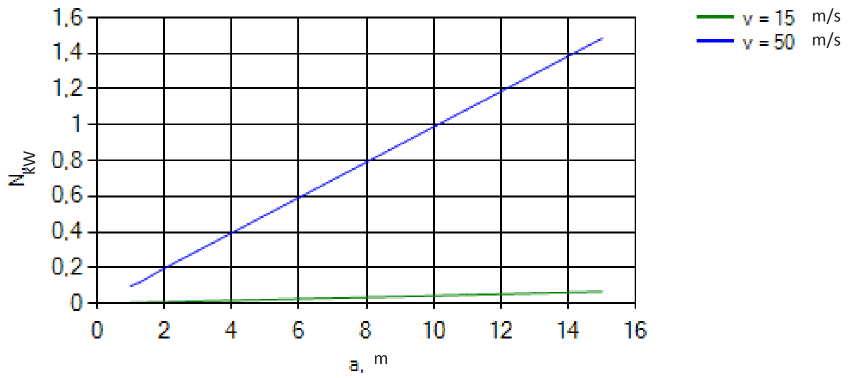
Results.

1. Schemes for changing the rotational regimes of the vortex generators that provide maneuvering of vessels, and the energy consumed for this.

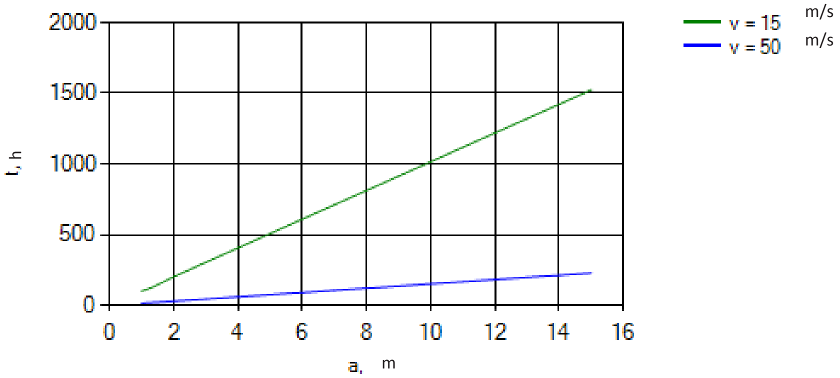
Since the speed vector $\vec{V}$ of the vessel is uniquely determined by the configuration of the flow of the «attached mass» of water in the closed region, the most natural way of affecting the vector is a change in the nature of the flow itself.

It is quite obvious that to change the speed of motion to the opposite one, it is sufficient to change the rotational speed of all the vortex generators to the opposite angular velocities, which is easily realized for both surface and underwater vessels. Schemes for changing rotor rotation for the correction of the velocity vector at angles other than π for surface vessels with two rotor pairs and for underwater vessels are presented in Table 1.

A change in the direction of the vector $\vec{V}$ by an angle π/2 (Table 1, line I) is achieved by reversing the rotation of two rotors arranged diagonally, i.e. rotors of various vortex. With this maneuver, the body of the surface vessel does not rotate and as a result moves «sideways». The spatial orientation of the vessel,



Pic. 2. Dependence of the specific (per running meter of the vortex generator) power transmitted to the medium by the smooth rotor of the vortex generator on the radius of the vortex generator.



Pic. 3. Estimation of time of unwinding of the attached mass by a smooth rotor.

including the rotor system of the vortex generators, does not change.

Rotation of the speed vector by an angle from 0 to $\pi/2$ (Table 1, line II) is achieved by turning all rotors in the same direction for some time τ. In this mode, the vessel, as a whole, acquires the angular speed of rotation ω^*, which is opposite to the rotor speeds ω. For more precise adjustment (ω^*) in one direction, not all, but any uncompensated number of rotors can be rotated. As a result, the vessel turns on an angle $\varphi = \omega^* t$.

Since the speed vector of the underwater (toroidal) vessel is oriented perpendicular to the median plane of the torus, to rotate the vector $\vec{V}$ by any angle other than π, the orientation of the median plane should be changed. To do this, it is sufficient to change the rotation mode of the diametrically opposite sections of the rotating shell of the underwater vessel (Table 1, line III). Rotation of a vessel as a whole by a certain angle is a time-consuming process, in contrast to maneuvering with a change in the direction of the vector $\vec{V}$ at angles π and $\pi/2$, representing a set of discrete individual actions (stopping and spinning of the rotors).

The maneuver with rotation to angles $0 \le \varphi < \pi/2$ of surface and to arbitrary angles of underwater vessels is complicated by the need to take into account the inertia that the rotational mode of the rotors initiating the turn of the vessel must be slowed down or stopped before reaching a given angle of rotation so that this rotation angle to be achieved by inertia.

Energy costs per maneuver in the first approximation are equal to twice the value of the kinetic energy in the region of closed flow of generators of all vortex pairs. This is due to the fact that to reduce the time of maneuver, any change in the rotation mode implies first a forced stop of the rotation of water established before the start of the maneuver, and then unwinding in a new direction.

2. Limit estimates of a closed flow formation time.

The initial data for the limit estimates of the formation time of a closed flow in the vicinity of a vortex propulsion unit are the kinetic energy of the attached mass of the medium in the steady-state mode E and the power P transmitted to the medium from the vortex generator performed by several (at least two) design schemes.

The minimum power transmitted to the liquid corresponds to the case of a smooth cylindrical rotor of diameter $d = 2a$ rotating in water with angular speed ω. An estimate from above of this power is the case of rotation in immobile water.

Force acting on one running meter of the rotor [9]:

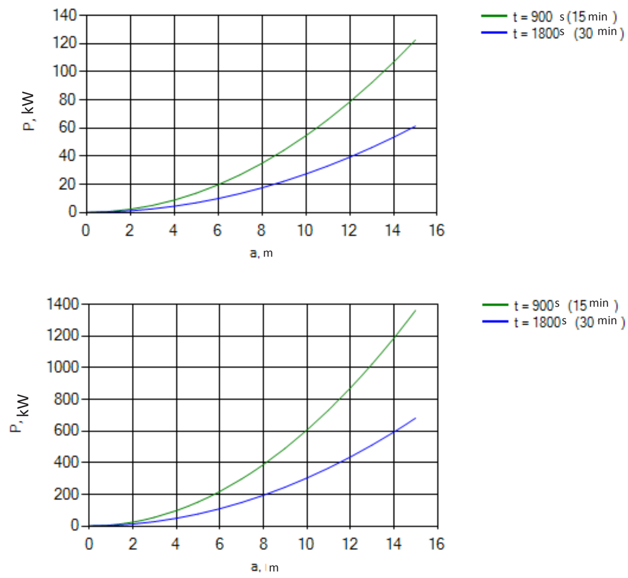
$$F_m = \mu\, 2\pi a \,\mathrm{grad}\, u, \quad (2)$$

where μ – dynamic viscosity of the fluid, and the maximum speed gradient is defined as follows [10]:

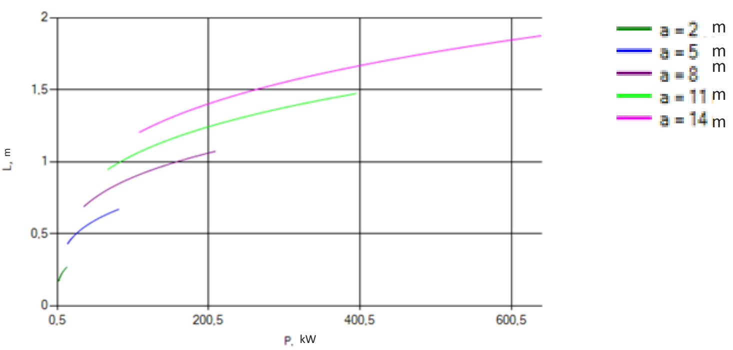
$$\mathrm{grad}\, u = \frac{v_{max}}{\delta}. \quad (3)$$

The thickness of the boundary layer δ is estimated from relation a)

b)



Pic. 4. Dependence of the power consumed on the radius of the rotor for a given unwinding time (a – for a surface vessel, b – for an underwater vessel).



Pic. 5. Dependence of width of the longitudinal blade on the power required to accelerate the attached mass.

$$\delta = \frac{L}{\sqrt{\mathrm{Re}}}, \quad (4)$$

where L – characteristic linear dimension of the streamlined body, Re – Reynolds number, which is defined by formula

$$\mathrm{Re} = \frac{2\pi a \, \rho \, u}{\mu}. \quad (5)$$

However the value grad u decreases in proportion to the distance from the rotor surface, so we take as an average estimate $grad\, u = \frac{v_{\max}}{a}$.

The power consumed at the stage of unwinding of rotors can be estimated from the following relationship:

$$N = F_{mp} v_{max} = \mu \, 2\pi a \, grad\, u. \quad (6)$$

Pic. 2 depicts the dependence of the power transmitted to the immobile water on the rotor radius, and Pic. 3 – estimation of the unwinding time of the attached mass $t = E/N$. It can be seen that this option is practically unacceptable.

Another estimation of the power that ensures the unwinding of the attached mass can be made by setting an acceptable time t, which is necessary to start motion, on the order of 30 minutes. Pic. 4 shows the calculated dependencies of the required power for acceleration time of 15 and 30 minutes.

The simplest way to transfer such increased power is to introduce one or more blades into the design. In the case of a single blade oriented in the radial direction of the rotor, while the length of the rotor forming a length equal to the length, the force acting on it when the rotor rotates in immobile water is:

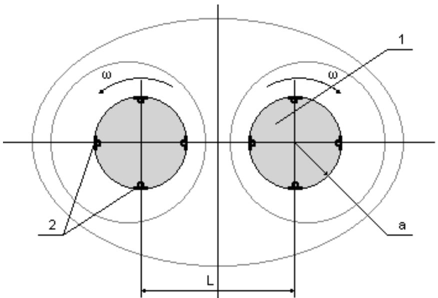
$$F_{bl} = \frac{\rho v^2(r)}{2} S, \quad (7)$$

where $v(r)$ – local linear speed of a blade, equal to ωr; r – radial coordinate of a blade; S – its area. Accordingly, maximum power transmitted by a blade to water:

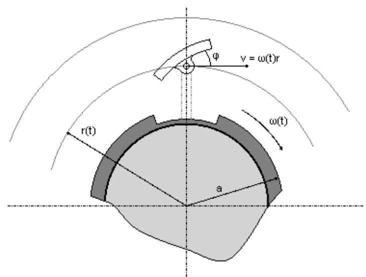
$$P = F_{bl} v(r) = \frac{\rho v^3(r)}{2} S. \quad (8)$$

Pic. 5 shows the dependence of width of one blade, capable of transmitting the previously determined power L(P) to water, for different radii of rotors.

It can be shown that the power transmitted by the blade, i. e. the amount of water required for reconstructing the flow of water in the closed flow region is at least an order of magnitude less than the power required for a traditional split design «body–propulsion unit» to overcome drag with a cross section



Pic. 6. Schematic diagram of the controlled block of retractable blades:
1 – rotor of the vortex generator, 2 – blades in the steady-state motion mode, a – rotor radius, L – distance between the rotors.



Pic. 7. Scheme of a rotor with a retractable blade.

of the body of the order of a^2 and is estimated by the ratio of the width of the blade to this transverse dimension, i.e. s/a.

1. Controlled block of retractable vanes with adjustable angle of attack.

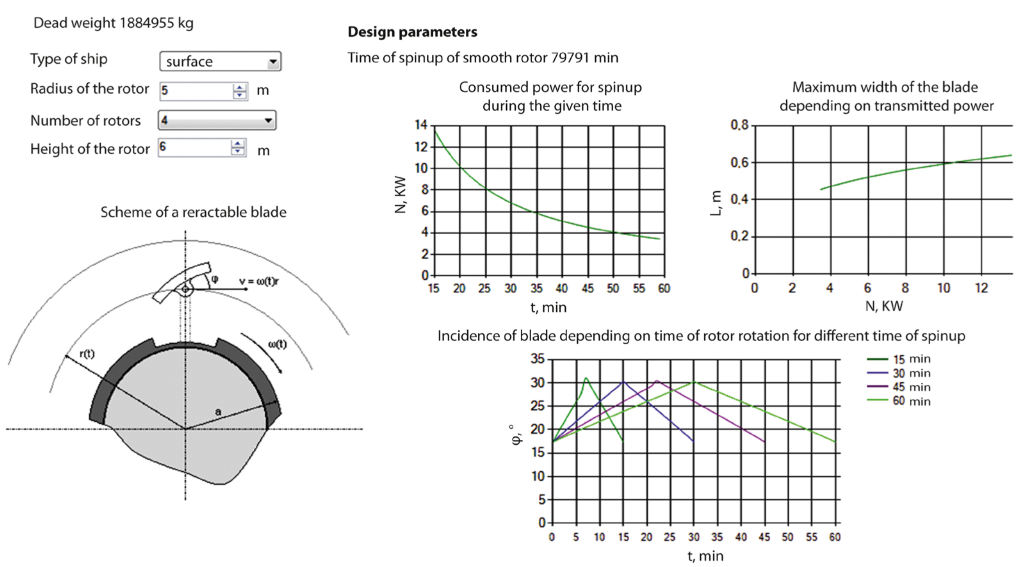
The blade with the dimensions defined in the previous section only transmits the calculated power to water only at the moment of starting the rotation of the rotor when water is stationary relative to the blade and the speed head is determined by the speed of blade motion. As water disperses, speed of the blade relative to it decreases by the speed of water and, accordingly, the speed head of the medium and the power transmitted to the water decrease. It is impossible to compensate for the decrease in the speed head by increasing the speed of the blade, since the linear speed of the blade should not differ significantly from the local water speed in the steady state. The most obvious way to increase the transmitted power in a continuously decreasing difference in blade and water speeds is to increase the effective area of the blade. In addition, it is relatively clear that the radius of rotation of the blade should not remain unchanged during the entire unwinding time of the attached mass, since the transmission of the impulse directly by the blade to the individual layers of water is more effective than the transmission of this pulse from one of the rotors due to viscosity. In other words, the effective unwinding of the attached mass by any mechanical device of invariable configuration is impossible.

Pic. 6 is a schematic diagram of a controlled set of retractable blades with an adjustable angle of attack.

In the initial state, the blades, made in the form of long and relatively thick plates, are located in the recesses (grooves) of the outer surface of the rotor of the vortex generator, so that one of their lateral surfaces is flush with the cylindrical surface of the rotor (Pic. 7).

Each of the blades is fastened to the end of the retractable rod. The rod length in the radial direction is somewhat (approximately the width of the blade) less than the distance from the rotor surface to the nearest boundary of the closed flow region.

Unwinding of the «attached mass» by the described blade block is carried out as follows. To drive the rotor with a blade block, a fixed-power motor is used, which is set by the time of unwinding. The rotor shell is driven into rotation with a calculated angular velocity ω_0. The software-controlled mechanism for extension of the rods rotates the blades so that the effective flow area of the latter corresponds to the design width of the single blade defined in point 2 (option – the blade is



Pic. 8. The window of the application, which simulates the algorithm of the mechanism of unwinding of the «attached volume» of the medium.

oriented either by force of resistance or by power). The speed of blade extension and subsequent retraction is determined by the set up time t: half the time – for extension and the same for return.

During the unwinding process, the rotor's angular velocity changes according to the law $\omega = \omega \cdot a/r$, where r is the instantaneous value of the radius where the center of the blade is.

The control of the described blade block is made by comparing the program (calculated) power values used for water dispersal, the position and orientation of the blades, the angular rotational speed of the rotor, the water velocity at various points in the closed flow region, and their actual (measured) values.

2. Development of software for modeling the mechanism of unwinding of the «attached volume» of the medium.

The above graphs are valid for a narrow class of vessels with certain overall characteristics. Obviously, a tool kit in the form of software is needed that allows to obtain estimated characteristics of the output to a stationary (cruising) mode based on a given type of vessel (surface or underwater) and its overall dimensions (displacement). On the basis of the stated mathematical apparatus, it is possible to form an algorithmic sequence of calculation of characteristics that can be used in vessel's control. Pic. 8 shows the window of the application being developed.

Programmed control should be based on the fact that the effective width of the blade, corresponding to the angle of attack at each instant of water unwinding time, is determined on the basis of the measurements obtained from the sensors or the force acting on the blade or the power expended on the blade movement in water.

For each vessel size there is a blade width sufficient for the vessel's acceleration in a minimum time. This width may be unacceptable for the design of the rotor, since the width of the blade should be much less than the radius of the rotor ($L << a$). If this condition is not estimated (with insufficient power), it is necessary to use several blades in the rotor design, which will reduce their width. At the same time, in the control process, one should take into account the synchronism of their extension and the change in the angles of attack of each for the optimal power consumption for unwinding of the attached mass of water.

Conclusions.

The computational and theoretical modeling of the maneuvering processes of water vessels with vortex propulsion units was performed:

– hydrodynamic principles of vessel's maneuvering by changing the rotation modes of individual elements of the vortex generators are formulated;

– it is shown that for effective use of vortex propulsion units for large-sized underwater and surface vessels, special measures are necessary to ensure the dispersal of water in the closed flow region («attached mass») in a predetermined and acceptable time, which in turn requires implementation of the operating mode of the propulsion unit, which is substantially different from its load when the vessel moves at a steady speed;

– for vessels with vortex propulsion units, the necessity of using special devices for unwinding of water in the closed flow area («attached mass») is justified when the vessel moves from a resting state to a steady-state mode;

– a constructive scheme of a controlled block of retractable blades with a variable angle of attack mounted on the rotor of the vortex generator is provided, which ensures a change in the flow regime of the «attached mass» of water for a given time;

– it is shown that the power required to perform maneuvers of vessels with vortex propulsion units (necessary in relatively short intervals of time) does not exceed the power necessary to overcome the drag of traditional layout vessels of the same displacement;

– software was developed to evaluate the mode of unwinding of the «attached volume» of the medium; simulation of distribution of water speed in the closed flow region made it possible to form control dependences – the values of the blade's attack angles from the predetermined time of the change in the flow regime of the «attached mass» of water.

REFERENCES

1. Ostroukhov, N. N., Chumakova, E. V. Vortex Propulsion Units of Sea Vessels and Aircrafts. *World of Transport and Transportation*, Vol. 14, 2016, Iss. 6, pp. 86–91.

2. Nedorub, S. A., Ostroukhuv, N. N. Propulsion unit of a transport vehicle. USSR patent No. 1533948, appl. No. 4286395/27–11 dd. 17.07.1987. Publ. 07.01.1990 [*Dvizhitel' transportnogo sredstva. Patent SSSR № 1533948, zayv. № 4286395/27–11 ot 17.07.1987. Publ. 07.01.1990*].

3. Ostroukhuv, N. N., Chumakova, E. V. Underwater or air (airship) vessel. Application for invention № 2017122033dd. 22.06.2017 [*Podvodnoe ili vozdushnoe (dirizhabl') sudno. Zayavka na izobretenie № 2017122033 ot 22.06.2017*].

4. Simanovich, A. I. Design of a body of a commercial vessel [*Konstruktsiya korpusa promyslovyh sudov*]. Moscow, Mir publ., 2005, 584 p.

5. Sedov, L. I. Continuum mechanics. Vol. 2 [*Mehanika sploshnoi sredy. Tom 2*]. Moscow, Nauka publ., 1970, 568 p.

6. Lamb, H. Hydrodynamics [*Gidrodinamika. Transl. from English*]. Moscow, OGIZ publ., 1947, 929 p.

7. Faber, T. E. Fluid Fluid Dynamics for Physicists. Cambridge University Press, 1995.

8. Sir Thomson W. (Lord Kelvin). The translatory velocity of circular vortex ring. *Phil. Mag.* (4), 1867, Vol. 33, pp. 511–512.

9. Kochin, N. E., Kibel, I. A., Roze, N. V. Theoretical hydromechanics. Part 1 [*Teoreticheskaya giromehanika. Chast' 1*]. Moscow, 1963, 584 p.

10. Schlichting, H. Boundary-layer theory. New York: McGraw-Hill, 1979, 817 p. ●

Information about the authors:

Ostroukhov, Nikolai N. – Ph.D. (Physics and Mathematics), senior researcher, associate professor at the department of applied mathematics, IT and electrical engineering of Moscow Aviation Institute (National Research University) (MAI), Moscow, Russia, vtvnukde@mail.ru,

Chumakova, Ekaterina V. – Ph.D. (Physics and Mathematics), associate professor at the department of applied mathematics, IT and electrical engineering of Moscow Aviation Institute (National Research University) (MAI), Moscow, Russia, ekat.v.ch@rambler.ru.

Article received 24.08.2017, accepted 21.10.2017.