Modelling of maneuvering of the ship equipped with two azipods

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Abstract. Wide development of the Northern Sea Route is one of the main national projects of the Russian Federation. Solution of this large-scale problem is impossible without new types of ships, which are capable of working all year round among ice of polar latitude. These vessels are designed for different purposes, so that they are characterized by stronger hulls of ice class and new types of propulsion device – azipods, in other words – screw-steering columns. Rotating of azipods along vertical axis allows to direct propulsive force in arbitrary direction, which makes it possible to stop using rudder and move more efficiently. For example, proceed forward with stern of the ship. Ships with two azipods are of special effectiveness. With wide operation of new types of propulsion devices, it becomes necessary to include their particular mathematical models in general model of the vessel. This as well applies to azimuthal propulsion devices, known as screw-steering columns. Model becomes more complicated when the ship is equipped with two azipods, which influence each other during application in a particular way. The practicable way of research of such ships’ work is their mathematical modelling, which includes modelling of the hull of the ship, as well as the azipods the ship equipped with. Exactly this model is described in this research. The vessel with displacement of about 36000 tons is equipped with two azipods. Hull is described by the model in shifts, work of every azipod – by Hoffmann algorithm. Basic value of propulsion force of every screw of azipod before its turn is calculated with Lammeren curve of screw force.

1. Essence of modelling

Further calculations, associated with azipods’ turn and change of conditions of flow along blades of the screw, are based on approximation of curves, given in reference book by A.D. Hoffmann. Computer research of the model consists in arbitrary manoeuvring of the ship with acquisition of all the features, kinematic ones (linear and angular velocity) and force ones (forces and moments). This is carried out for the hull of the ship and for the every azipod in particular. The results are presented as a set of graphs and conclusions, made on basis of analysis of obtained model data. Modelling is performed with software package of the authors of the article, registered №2018666912 in Federal Service of intellectual property on 24.12.2018. The manoeuvring itself is performed in interactive part of the program, and after the end of manoeuvring all the necessary characteristics are saved as files. Afterwards, files are analyzed and results are put into shape of graphs in other part of the software package. Software package is implemented in two different computer modes – Visual Basic 6 and MathCad.

For algorithmization of the calculations related to only one azipod, there are special computing schemes - for example, Hoffmann algorithm [1]. For the systems with two azipods this scheme is repeated twice, one time for each azipod. Even this method allows to take into consideration the
influence of one azipod on another one since change of conditions of flow along blades of the screw takes place while first azipod is turned, and vice versa. For that goal we need to calculate the parameters of flows along blades of each azipod, taking into account the coordinates of their disposition behind the hull. Modelling of the operation of two azipods complicates the graphical interface of the program. There is a joystick for each azipod, which allows to operate actual power of the screw and angle of azipod rotation. Dynamic change of these parameters occurs according to real rate of their change in ships’ practice. Power is converted into revolutions of screw, which are regulated by revolution stabilization system afterwards. Therefore, three differential equations of motion of model of the vessel (longitudinal, transversal linear velocity, angular velocity of ship’s turn) are joined by two differential equations of screw rotation in liquid medium with accounting of moment of inertia of added masses of the ship. All above–listed information gives opportunity to research revolution stabilization systems in alternating conditions of manoeuvring (e.g. during circulation with influence of wind) with the help of this model.

2. Trial of ship’s models
All research work was carried out on basis of the software package of the authors of the article, registered №2018666912 in Federal Service of intellectual property. Package consists of two parts, first one being a convenient graphical interface, which allows to choose size of the water area, the initial position of the vessel and afterwards launch the trial program for every vessel, if the hull model of the ship was calculated and disposed in database before. Then the actions of the ‘navigator’ can be different. Those actions include controlling of the propulsion device by defining the actual power which is transferred to screw of every azipod and turning azipods at arbitrary angles to the diametral plane of the ship. Trajectory of the vessel under those parameters is shown on area of water (Figure 1). In dynamic mode values of the typical kinematic and force parameters of maneuvering are shown in wide range in text boxes. Rate of modelling can be accelerated up to 64 times and slowed down up to 8 times. Although, monitoring of all the maneuvering parameters in the process of modelling is rather difficult since there are too many of them, and only their complex matters. Therefore, all the parameters are written in the arrays during every modelling cycle which means during every step of integration of system of differential equations. In the end of the process that allows to output necessary parameters from arrays to appropriate files, which afterwards are read and analyzed in the second part of the software package. Only after that actions instructive conclusions are made on the basis of group analysis of the results. The graphical part of the interface is shown in Figure 1: Azipod control unit (up on the right) against the background of water area, where the trajectory of the ship is shown with representation of the diametral plane of the ship after every 10 seconds of the integration. We can see that last maneuver implemented was the circulation of the vessel clockwise, and for that goal the portside azipod had been used with the actual power of 46,6% of nominal power and with angle of its deviation of 9 degrees starboard side. In fact, starboard side azipod was not working at that moment.
3. Differential equations of the task.
As already said before, task is defined by system of 5 differential equations of first order. Three first equations define the movement of the vessel, in this case shift system is chosen, which is shown by group of formulas (1). All the designations are quite conventional here, and we can relate to up-to-date article [2], where all the components of the equations are described. In this case force influence from azipods are important for us.

Figure 1. The interface of the ship control system (azipods, trajectory).
\[
\begin{align*}
(m_1) \left( \frac{dv_x}{dt} \right) &= -(m_{22}) v_x \varpi + \left[ \frac{C_{x1} - C_{x0}}{2} v_x^2 - \frac{C_{x1} - C_{x0} vv_y}{2} + b_1 v_y^2 + 2 b_2 \frac{v_x v_y^2}{v_x^2} \right] \frac{\rho A_{sr}}{2} + \\
C_{Ax} \rho_2 \frac{A_{sr} v_x^2}{2} - F_{rX} + T_e + F_X \\
(m_{22}) \left( \frac{dv_y}{dt} \right) &= -(m_{11}) v_y \varpi - 2 C_{yp} \frac{v_y^2}{v_x} + c_2 v_x \frac{v_y^2}{v_x^2} - 16 c_3 \frac{v_y v_x^4}{v_x^6} \frac{\rho A_{sr}}{2} + \\
C_{Ay} \rho_2 \frac{A_{sr} v_y^2}{2} + F_{rY} + F_Y \\
J \left( \frac{d\varpi}{dt} \right) &= \left[ 2 m_1 v_y v_x + m_2 v_y v_y + m_3 \frac{v_y^4}{v_x^2} - 16 m_4 \frac{v_y v_x^4}{v_x^6} + C_{M0} L^2 v_x \right] \frac{\rho A_{sr}}{2} + C_{AM} \rho_2 \frac{A_{sr} L v_y^2}{2} + M_r + M_z \\
\end{align*}
\]

Without change of notation, forces with low index ‘r’ will be attributed to azipods. These forces are \( F_{rX}, F_{rY} \) – longitudinal and transversal forces and torque moment \( M_r \). At that time thrust of the screw \( T_e \) is being excluded from first equation since it will be a part of the force \( F_X \) with a consideration of sense. So first three equations will formally not undergo changes, only ‘rudder’ forces will have different meaning.

Two equations left are the equations of screw rotation in liquid medium. They are structurally identical, but can have different setup values of power and revolution for account of control. First equation is shown in subprogram body of VB6, which defines increment of screw revolution in variable conditions of movement. The differential equation itself is:

\[
dNs = \frac{(ccc * Mdv - MyScrew.q)}{J} 
\]

where \( MyScrew.q \) – resisting moment of the screw in liquid medium, \( J \) – moment of inertia of the screw accounting added moment of inertia of water, \( Mdv \) – moment developed by electric motor of azipod:

\[
Mdv = aa^*sgn(MyScrew.ns)^*MyScrew.ns2 + bb^*(MyUst.ns - MyScrew.ns)
\]

Moment of the motor is calculated as proportional to squared screw revolution with regulating additive, which is proportional to difference of nominal revolution \( MyUst.ns \) and actual revolution \( MyScrew.ns \). That designation of parameters proves that software package widely uses object concept (screw MyScrew and revolution MyUst).

Differential equation of operation of the second azipod screw is absolutely similar, but it uses objects MyScrew2 and MyUst2, since every azipod can be operated independently. Moreover, switch from synchronous to asynchronous mode of operation is implemented into the program.

4. Integration of equation system.

All differential equations are solved by Euler method. Experience in solution of such problems with inertial objects (ship) shows that the method ensures necessary accuracy without need to use method of Runge-Kutta. Results of solution of the differential equations in format of increments to motion parameters are just added to previous values, e.g. for longitudinal velocity \( Vx=Vx + dVx \), and revolution of the screw \( ns = ns + dNs \). Moreover, all other variables of the problem are recalculated for new values of motion parameters in every cycle of the solution.

The most difficult thing in case of azipods is defining longitudinal and transversal forces \( F_{rX}, F_{rY} \) and torque moment \( M_r \) for every azipod. For that goal we use algorithm of Hoffmann A.D. [1]. Let us examine it with indication of changes made.

Advance of a propeller is calculated by formula:

\[
J = (1 - wt)^*V/(ns*D),
\]

where \( D \) – diameter of azipod screw, \( wt \) – coefficient of following current.
Coefficients of thrust $k_T$ and moment $k_Q$ of the screw are calculated by versatile action curves of the propeller by Lammeren [3, 4, 6], which is our main change in Hoffmann algorithm. It allows to define thrust and moment of the screw for different conditions of operation.

Let us calculate values of thrust and moment for axial accumulation of current on blades of the screw:

$$ T_0 = k_T \ast p \ast ns^2 \ast D^4, \quad Q_0 = k_Q \ast p \ast ns^2 \ast D^5. \quad (4) $$

Let us calculate the coefficient of thrust stress for axial accumulation:

$$ \sigma_T = \frac{(8k_T)}{(\pi J^2)}. \quad (5) $$

Following steps of the algorithm are related to rotating of the azipod, which causes the change of conditions of flow along blades of the screw, which leads to change of kinematic and force parameters. Hoffmann algorithm takes this rotation into account with the help of diagrams for coefficients $qR$ and angle $\theta$ of deviation of resultant force vector of azipod from its axis. This consideration has a format of function of angle $\Psi$ of leakage of current on the blades of azipod in range of $0^\circ$-$180^\circ$. Both parameters also depend on relative screw twist P/D, but we deal with curves which describe relations when P/D = 1.

Parameter of the chosen curves is a coefficient of stress on the thrust $\sigma_T$, which was calculated in the previous step by formula (5). That kind of calculation with the help of diagrams is possible only in the time of designing of the vessel with azipod, when the solution is carried out few times, during selection of the azipod. In our case it is necessary to have analytic formula for $qR$ and angle $\theta$ since all the calculations are repeated many times, in every cycle of the solution. Curves of A.D. Hoffmann are digitized with a special software and approximated in MathCad. These bivariate approximations are implemented as two subprograms of VB6 environment, where a part of software package for manoeuvring trial is executed.

For entering these functions we should determine the angle of accumulation $\Psi$, which is defined as difference between the angle of azipod turn $\delta$ and local drift angle $\beta_a^*$. Local drift angle without taking hull into account is defined with the help of tangent by formula:

$$ \tan(\beta_a^*) = \frac{(V_y - x_M \ast \omega)}{(V_x - y_M \ast \omega)}, \quad (6) $$

where $x_M$ and $y_M$ - coordinates of disposition of vertical azipod axis in the coordinate system linked with the ship. If azipod is located in the diametral plane of the vessel, then $y_M = 0$, but with two azipods their coordinates are not equal to zero and differ from each other with a sense. Then the angle $\beta_a^*$ is corrected with coefficient of kinematic interaction of screw with the hull $\chi$:

$$ \beta_a^* = \chi \ast \beta_a^*, \quad (7) $$

afterwards angle $\Psi$ is defined $\Psi = \delta - \beta_a^*$ for entering the function $qR_{from_ St_ Psi}$ and $Teta_{from_ St_ Psi}$.

Now we are able to calculate the value of resultant force $R$ of the propeller

$$ R = qR \ast T_0, \quad (8) $$

and angle of deviation of that force from diametral plane of the ship:

$$ \gamma = \delta + \theta. \quad (9) $$

This allows to define longitudinal and transversal forces, produced by rotated azipod:

$$ F_{X} = qR \ast T_0 \ast \cos(\delta + \theta) \quad F_{Y} = qR \ast T_0 \ast \sin(\delta + \theta) \quad (10) $$

and take them into consideration in two first differential equations of group (1). Let us add the last step of the algorithm – calculation of ship’s torque moment for the third equation from group (1):

$$ Mr = F_{X} \ast y_M + F_{Y} \ast x_M \quad (11) $$

All these steps of the algorithm are implemented for every azipod separately and during every cycle of integrating of the differential equations [5, 8, 9]. All the parameters of this algorithm, that is angles and forces are shown in Figure 2, where we can see azipod in the diametral plane of the vessel, rotated at angle $\delta$. 


Figure 2. The main geometric parameters of the design scheme by Hoffmann A.D.

- $\delta$ – angle of rotation of azipod,
- $\Psi$ - angle of accumulation of current,
- $\theta$ - angle of deviation of force $R$ from azipod axis,
- $\gamma$ - angle of deviation of force $R$ from diametral plane,
- $\varphi$ – angle of deviation of force $R$ from direction of the current,
- $\beta_m$ – local drift angle,
- $R$ – resultant force on azipod,
- $X, Y$ – projections of force $R$ on diametral plane and perpendicularly to it,
- $V_A$ – vector of accumulated current.

After having completed these steps, we are able to use software package for modelling any type of manoeuvring. The graphic interface of the package shown particularly in Figure 1 is used for operating the manoeuvres. As a result of manoeuvring, all the parameters that were changed during the process are subjected to analysis. For that goal we must run a subprogram by double-clicking left mouse button on a certain textbox of main manoeuvre form. This subprogram opens a file and records certain set of parameters in it (left-click of textbox $\text{lblAzip}$ records 16 parameters provided the ship is equipped with azipods). The subprogram works for one azipod as well as for two, and in that case it records the following parameters of manoeuvring:

- for the first azipod – forces $X, Y$; moment $M$; angles $\delta$ and $\gamma$, percentage of power, velocity $V_x$ and $V_y$, angular velocity of rotating $\omega$, thrust screw stress, angle $\theta$, relative advance of propeller $J$, coefficient $q_R$, угол $\Psi$, screw revolution $N_s$.
- the same parameters for the second azipod, but coordinates $X, Y$ and course of the ship $K$ are recorded instead of $V_x, V_y, \omega$. 
Figure 3 is a screenshot of interface form with hidden azipod control unit. Composite trajectory of manoeuvring is generated by constant rotating of the second azipod and arbitrary rotating of the first azipod. The aim of the trial is a demonstration of features of software package for obtaining parameters of manoeuvring with their further analysis. Particularly, to estimate influence of rotating the first azipod on the work of the second azipod.

All further actions related to analysis of the process of manoeuvring are carried out in MathCad environment. File, created in VB6, is read in MathCad in the form of matrix with 16 columns and with amount of lines equal to doubled quantity of cycles of integrating needed for solution of equation system (1). After reading the file in the form of matrix, it is divided into vectors for different parameters of manoeuvring. The trial is carried out for the tanker with displacement of 36000 tons, equipped with two azipods with power of 5400 kW each. Transversal coordinates of axes of azipods $y_M$ are $\pm 12$ meters with the diameter of the blades of 4 meters.

5. Results of modelling.
Further you can see part of the results of the trial in graphic form, which are most essential for our research. Our main goal is to estimate influence of one azipod on the work of another one. Therefore, in Figure 4 you can see the alteration of angle of azipods’ rotating during the trial. It is clear that the second azipod is at constant position for two prolonged periods, but meanwhile the first azipod is being variously rotated. We have the opportunity to control the change of parameters of the second azipod. So in the lower part of Figure 5 it is shown how the coefficient $Qr1$ is changed during rotating angle of azipod Alf1 is varied. It is obvious that coefficient $Qr1$, which determines forces on rotated azipod, considerably depends on the angle of rotating of azipod. Naturally, the coefficient unevenly changes when the angle of rotating of azipod is changed. But Figure 5 proves that there is no considerable relation between coefficient of the second azipod $Qr2$ and the angle of rotating of first azipod. This relation is very weak and indirect and appears due to change of conditions of flow along second azipod during the turn of the vessel. At the same time torque moments of azipods change almost coherently when only the
angle of rotating of first azipod is changed. Moments are considerably more sensible and alter unevenly almost simultaneously when only one azipod is being rotated.

Similar graphic relations are obtained for all the parameters in mathematical model, kinematic and force ones. They are not given here due to limitation of article size, but they are fully included in the report on the subject of research.

Figure 4. The change of the rotating of azipods during the trial (top, °); change of coefficient $Qr_1$ of the resultant force of the first azipod depending on the angle of rotating of the first azipod (bottom).
6. Conclusion.
On the basis of the conducted trial of the model and on the basis of the results in the graphic form we can draw following conclusions about the model and subject of research.
1. Mathematical model implemented in software is capable of working. It possesses convenient graphic interface for controlling the azipods of the vessel and allows to obtain the change of all the parameters of the vessel’s model during the process of manoeuvring.
2. Interface of the program allows to fulfil adjustment of the model due to implementation of special operating modes, when two azipods are operated independently, synchronously and anisochronously. This feature gives the opportunity to control the calculations of functioning every azipod separately as well as their collateral work [7].
3. It is shown that the work of one azipod influences the work of another through change in parameters of accumulating current. Every parameter does not change too dramatically when one azipod is rotated, but their simultaneous change considerably affects force characteristics of another azipod.
4. Resolution IMO №137 of 05.12.2002 [10] defines standard types of manoeuvres (acceleration, circulation, zigzag) for ordinary trial of mathematical model of the vessel, but for the case of the vessel with two azipods there are no such standards. The main objective is to create a set of base trials, which will at most discover potential of operating a ship with two azipods within functional goals of that particular type of ship. Of course, standard manoeuvres will be included in the set, but lots of combinations of azipod rotating and stress will create new manoeuvres as a result. They will be developed and implemented in the model during the process of further research on the topic.

References
[1] Hoffmann A D 1988 Maneuvering of the vessel and propulsive-steering complex. Reference book Sudostroenie 134-160
[2] Pashentsev S V 2017 Comparative analysis of mathematical models of the vessel in the aspect of maneuverability by deviations Vestnik Murmanskogo Gosudarstvennogo Tekhicheskogo Universiteta. 20(4) 671-680
[3] Lammeren W P A 1969 The Annual Meeting, N.Y. The Society of Naval Architects and Engineers 26-59
[4] Pashentsev S V 2018 Modelling of cyclic bidirectional movement of the vessel with the use of modified action curves of screw by Lammeren Vestnik Murmanskogo Tekhicheskogo Universiteta 21(4) 566-576
[5] Voytkusniy Y I 1985 Reference book on the theory of the vessel Sudostroenie 1 470-489
[6] Lammeren W P A 1957 Resistance, propulsive characteristics and manoeuvrability of vessels. Reference book Izdatelstvo sudostroitelnoi promyshlennosti. 55-114
[7] Makedonov I 2016 Development and research of screw-steering column Lamber Academic Publishing 71-80
[8] Sizov V G 2004 Theory of the vessels Feniks 44-101
[9] Zhinkin V B 2002 Theory and structure of the vessel Sudostroenie 166-217
[10] Maritime Safety Committee 2002 Resolution MSC.137(76). Standarts for ship manoeuvrability IMO 1-8