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Modelling cyclic reverse movements of the vessel using modified Lammeren's curves of screw action

In our national practice, the screw action curves are traditionally used either for positive values of the screw speed n and the vessel's velocity v, or when one of these characteristics of the movement is negative. Consequently, the used curves of the screw action do not allow to create computer simulators for testing specific maneuvering tasks with reversible moves. The purpose of the work is to study the opportunities of mathematical modelling of the vessel's reverse movements, when the propeller advance of the fixed pitch screw is constantly changing. In foreign sources, really universal Lammeren's curves of screw action can be found. The specificity of these curves is that the introduction to them is performed not due to the pitch ratio itself, but due to the angle β of the direction incident to the propeller blade. This angle is determined by using tangent tg(β) = $v/(0.7\ \pi nD)$, and it is sensitive to the change of sign of both the ship's velocity v and the revolution speed n. Therefore, these curves are presented as functions of the angle β in the range of angles 0°–360°. These curves are obtained and described by Lammeren as the results of processing experimental data concerning the thrust and the screw torque and are approximated by Fourier series, in which 20 terms are kept. These curves can be used as universal ones. This allows to integrate a system of two equations: the motion of the vessel and the rotation of the screw with arbitrary signs of these movements' direction by means of MathCad. By setting the law regulating the speed of the ship engine, it is possible to simulate arbitrary maneuvers of the vessel with any change of direction. The considered approach to modeling has been tested in the paper and implemented in the interface control for vessel maneuvering within the computer simulator.

Key words: reverse propulsion, mathematical modelling, the curves of screw action, Lammeren's curves of screw action.

Introduction

Over the years screw action curves have been used for solving problems connected first of all with the ship's propulsion. In these calculations the ship's velocity and the screw speed are positive, and the advance ratio does not change its sign. Therefore, only the action curve in the first quadrant has been used where "advance ratio is thrust and torque ratios". In modern conditions, when the hydrocarbon production is carried out offshore, the problem of maneuvering vessels with changing the direction of screw rotation and reversing has become extremely acute. This is a characteristic of maneuvering tankers at the oil loading terminals or during dynamic positioning of drill ships at the drilling site. It should be noted that the screw action curves which have been used in Russian research might be named semi-universal. For this particular reason such modified advance ratios as "Lavrentiev advance ratio" $J_{Л}$ and "Hoffman advance ratio" $J_{Г}$ have been introduced [1]:

$$J_{Л} = \frac{v_A}{\sqrt{(v_A)^2 + (nD)^2}}; \qquad J_{Г} = \frac{nD}{\sqrt{(v_A)^2 + (nD)^2}}.$$

The former one solves the problems of changing the sign of ship's velocity, the latter deals with changing the sign of screw speed. And even though the advance ratio curves are plotted for them, they do not solve the problem of arbitrary combinations of the ship's velocity and screw rotation signs.

The main objective of this research is the development and improvement of computer simulator programmes which allow to practice maneuvering of the above types. Accordingly, the purpose of this work is investigating the perspectives of mathematical modelling of vessel's reverse movement with constant changing the advance ratio of a fixed pitch screw. In foreign sources [2], Lammeren's action curves are mentioned as the result of systematic B-series screws tests in Wageningen Ship Model Basin (the Netherlands). The specificity of these curves is that the introduction to them is performed not due to the pitch ratio itself, but the angle β of the direction of the flow running onto the blade. This angle is determined by using tangent tg(β) = $v/(0.7\pi nD)$. It is sensitive to the change of the sign of both the ship's velocity v and the revolution speed n, if the inverse tangent is calculated taking into account the quadrant of its solution. Therefore, these curves are presented as functions of angle β in the range of angles 0°–360°. They are obtained and described by Lammeren as the results of processing experimental data concerning the thrust and the screw torque and are approximated by Fourier series with 20 terms. These curves can be used as universal ones, which allows to integrate a system of two equations – the motion of the vessel and the rotation of the screw with arbitrary signs of the direction of these movements – by means of the MathCad package. By setting the law regulating the speed of the ship's engine, it is possible to simulate arbitrary maneuvers of the vessel with the direction change of the vessel's movement and screw rotation. Further, this approach to modelling implemented in the interface maneuver control of a computer simulator has been developed.

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Materials and methods

How to obtain Lammeren's curves of the screw action was presented in detail in the proceedings of the Annual Meeting of the Society of Naval Architects and Engineers in New York in 1969 [2]. The authors point out that the researches in this area which they are familiar with [3–5] concern special cases of constructing the curves of screw action. They also offer a universal approach to this problem. Further, in their work, the action curves are represented in the form of the Fourier series with 20 terms of 4-blade B-series screws for a number of values of pitch ratio *P*/*D*.

We have chosen a pitch ratio equal to 1 for certainty, although all further decisions and principal conclusions are valid for any value of *P*/*D* in the range 0.6–1.4. Fig. 1 shows Lammeren's curves of the screw action as a function of the angle β, the angle itself is determined by its tangent:

$$tg(\beta) = \frac{v}{0.7\pi nD}. \tag{1}$$

Although such a universal curve is of great interest, there are some doubts concerning its correctness. First of all, attention must be paid to the fact that nothing is said about it in our classic reference books [1; 6] widely used by both shipbuilders and specialists engaged in the operation of ships. Also, a simple visual analysis of the curves in Fig. 1 suggests that they do not quite correspond to reality. Indeed, if we take the positive values of the speed of the ship and the rotation speed of the screw, we get the value of the angle β according to the formula (1) in the first quadrant (which is indicated by the author himself). But in the first quadrant, the screw thrust and torque coefficients take negative values. This is fundamentally counterintuitive – in this case, they should both be positive. Similar contradictions arise in the other quadrants of the angle β. Of course, when taking arctangent, some amendments on quadrant can be introduced, but the materials [2] say nothing about it. For more valid conclusions we should consider Table 1 where we give the values of the coefficients of the propeller thrust *CT* and torque *CQ* for all the quadrants of the angle β. This is done for the initial curve in Fig. 1 (Lammeren), for the modified curve (Fig. 2) using the shift of the original curve (Lammeren Shifted), for shifted and smooth curve (Lammeren Smooth) in Fig. 3 for eliminating dips in the coefficients in the areas of transition the angle β = 90° and β = 270°.

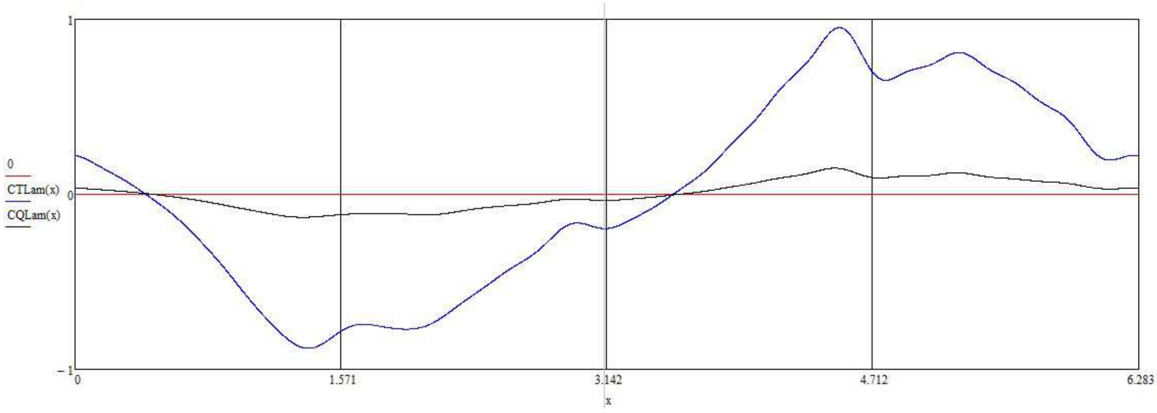

Fig. 1. The initial Lammeren's curves of screw action
Рис. 1. Исходные кривые действия винта Ламмерена

In order to eliminate dips, the pair of characteristics – the velocity *v* and the screw revolution speed *n* – the values that translate the angle β in the desired plane were given. After that, with the help of MathCad "Tracing" tool, where the graphs were built, the values of the coefficients *CT* and *CQ* were defined. All these data are listed in Table in the relevant sections. A simple view of the results shows the inconsistency of the values in the first paired row. These contradictions are eliminated by shifting (the second pair line), and smoothing eliminates dips. It is the last representation of the Lammeren's curve that we will use in the future solution. In order to enter the curves the angle has to be calculated in a certain way using the built-in MathCad function angle(), which is as follows:

$$\beta e(v,n) := \left| \begin{array}{l} be \leftarrow angle\left[v,(0.7\pi \cdot n \cdot D)\right] \\ return \;\; be \end{array} \right. . \tag{2}$$

Table. *CT* and *CQ* coefficients of the screw for all the angle β quadrants
Таблица. Коэффициенты *CT* и *CQ* винта для всех четвертей угла β

v / *n*		+1 / +1	–1 / +1	–1 / –1	+1 / –1
	Angle β, rad.	1.341	1.801	4.482	4.942
Lammeren	*CTL*	–0.875	–0.754	0.942	0.710
	CQL	–0.132	–0.109	0.149	0.104
Lammeren Shifted	*CTL*	0.214	0.114	–0.176	–0.100
	CQL	0.033	0.021	–0.028	–0.020
Lammeren Smooth	*CTL*	0.324	0.110	–0.265	–0.114
	CQL	0.037	0.024	–0.037	–0.021

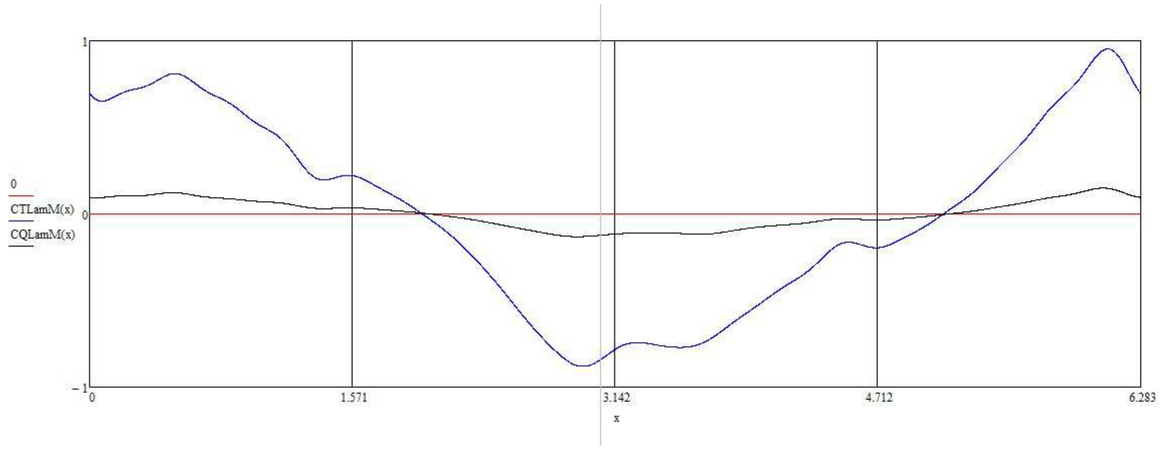

Fig. 2. Shift-modified Lammeren's curves of the screw action
Рис. 2. Модифицированные сдвигом кривые действия винта Ламмерена

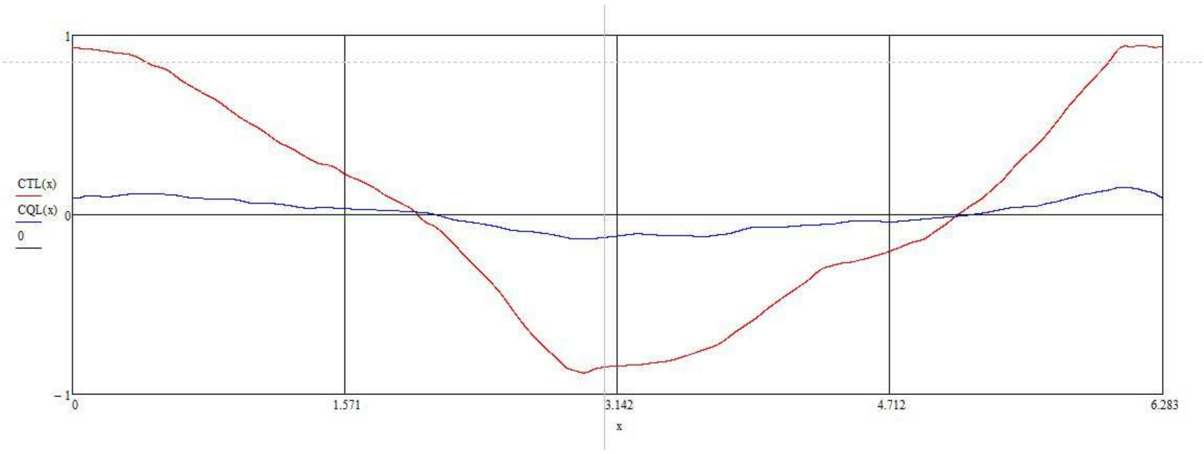

Fig. 3. Modified and smoothed Lammeren's curves of the screw action
Рис. 3. Модифицированные и сглаженные кривые действия винта Ламмерена

Differential equations of the problem

The solution is made in MathCad which provides ample opportunities for integrating systems of differential equations and then obtaining high-quality graphic materials. In fact, we are to integrate a system of two differential equations.

The first one is the equation of rectilinear motion of a vessel which is affected by the hydraulic resistance force and the screw thrust. The force of resistance will be considered proportional to the square of the movement speed and always opposed to the movement. It is the force of the screw thrust that we find with the help of the modified and smoothed Lammeren's curve. To do this, *CT* coefficient of the propeller thrust is taken from the curve, then according to Lammeren the thrust is found using the formula:

$$TT = (1-t)\cdot CT\cdot (v^2 + (0.7\pi nD)^2)\frac{\pi\rho D^2}{8}. \tag{3a}$$

During the calculation the resistance augment fraction t is assumed to be equal to zero. This is done to simplify the formulae recording and does not change the fundamental conclusions.

The second equation describes the rotation of the propeller on a moving ship. The rotation of the screw is provided by the engine torque $Mdv(t, n)$, and the torque of the screw represents the antitorque moment. For this the torque coefficient CQ is taken from the curve. Then, the torque is found by the formula:

$$QQ = CQ \cdot (v^2 + (0.7\pi n D)^2)\frac{\pi\rho D^3}{8}. \tag{3b}$$

In order to obtain two differential equations for the linear acceleration of the vessel dv_1 and the angular acceleration of the screw dn_1 we are to: 1) divide the sum of forces by the mass of the vessel taking into account the virtual mass of entrained water MM, and 2) divide the sum of torques by the moment of the rotating parts inertia with the account of the virtual mass moment of water inertia JJ:

$$\begin{aligned} dv1(v,n) &:= \frac{-kV(v)\cdot v\cdot |v| + kT\cdot TT(v,n)}{MM}; \\ dn1(v,n,t) &:= \frac{kM\cdot Mdv(t,n) - kQ\cdot QQ(v,n)}{JJ}. \end{aligned} \tag{4}$$

In addition to specifying the differential equations themselves, it is necessary to determine the law of change in the screw rotation speed by means of the control system. For this purpose, the time-dependent function of statutory revolutions $nUst(t)$ has been introduced. In our research, the periodic time function with the period T_0 = 1 200 s (20 min) has been chosen.

$$nUst(t) := \left| \begin{array}{l} nU \leftarrow n0\cdot\cos\left(\dfrac{2\pi t}{T0}\right). \\ return\ \ nU \end{array}\right. \tag{5}$$

The function is recorded in the MathCad programme function. The statutory function (5) is included in the law of changing the torque of the ship's engine $Mdv(t, n)$ and allows to maintain the screw speed at the given set level. For the regulation law, the parameters aa = 2 100, bb = 100 are chosen. This provides the regulatory characteristic close to the vertical curve in the $m – n$ (torque – rpm) axes.

$$Mdv(t,n) := aa\cdot sign\big(nUst(t)\big)\cdot nUst(t)^2 + bb\cdot(nUst(t) - n). \tag{6}$$

The first equation (5) takes into consideration the effect of diffferent hydraulic resistance while moving ahead or astern. It is done in the form of MathCad function for resistance coefficient:

$$kV(v) := \left| \begin{array}{l} kv \leftarrow kV0\ \ if\ \ v > 0 \\ kv \leftarrow kV0\cdot 1.2\ \ otherwise. \\ return\ \ kv \end{array}\right. \tag{7}$$

All the constants are to be established at the beginning of the integration process. Their values are given in the groups of equations (8) where the values of all the constants correlate with SI system, except for MM mass which is traditionally presented in tonnes.

$$\begin{array}{ll} T0 = 1\,200\quad n0 = 120/60\quad v0 = 4\quad D = 6.1\quad \rho = 1.025 & \\ aa = 2\,100\quad bb = 100 & \\ MM = 24\,000 & JJ = 10\,000 \\ kT = 1 & kQ = 1 \\ kV0 := \dfrac{kT\cdot TT(v0,n0)}{v0\cdot|v0|} & kM := \dfrac{kQ\cdot QQ(v0,n0)}{Mdv(0,n0)} \end{array} \tag{8}$$

Integration of the equations' system

The solution of the system (4) is performed using a built-in function rkfixed() of MathCad and is shown in Fig. 4. In two initial lines, the right-hand members of the differential equations of v and n system are repeated. In MathCad syntax, these variables become components of a column vector that is shown in a transposed form. The number of integration steps is chosen to be 2 048 = 2^{11} so that the fast Fourier transform (FFT) can be used later. The vector of derivatives is given by the expression $P(t, y)$, where the components are represented by the functions of y vector. The appeal to the Runge – Kutta integration function Z = rkfixed(y, 0, m, m, P) performs the procedure of solving the system of differential equations. The solution results are interpolated in the matrix Z, which in this case consists of three columns and 2048 rows. The first column contains the current integration time, the other two columns are the vessel velocity v and the screw revolution speed n. These columns are extracted by simple assignment from the matrix Z in the form of V and N vectors in the last two lines of Fig. 4.

$$\mathrm{dv1}(v,n) := \frac{(-kV(v)\cdot v\cdot |v| + kT\cdot TT(v,n))}{MM}$$

$$\mathrm{dn1}(v,n,t) := \frac{[kM\cdot(Mdv(t,n)) - kQ\cdot QQ(v,n)]}{JJ}$$

$$y := \begin{pmatrix} v0 \\ n0 \end{pmatrix}$$

$$P(t,y) := \begin{pmatrix} \mathrm{dv1}(y_0, y_1) \\ \mathrm{dn1}(y_0, y_1, t) \end{pmatrix}$$

$$m := 2048 \quad k := 0..m-1$$

$$Z := \mathrm{rkfixed}(y, 0, m, m, P)$$

$$V := Z^{\langle 1\rangle} \qquad N := Z^{\langle 2\rangle} \qquad T := Z^{\langle 0\rangle}$$

$$Tt_k := TT(V_k, N_k) \qquad Qq_k := QQ(V_k, N_k)$$

Fig. 4. Differential equations of the ship's movement and the screw rotation,
and their integration by means of rkfixed() function
Рис. 4. Дифференциальные уравнения движения судна и вращения винта
и их интегрирование с помощью функции rkfixed()

Solution graphics

In Fig. 5 there are two obtained vectors V and N represented graphically. The periodic change in these characteristics of movement is clearly visible, and the rotation speed is ahead of the ship's velocity at the point of transition through the zero values – the engine inertia is less than the vessel one. Thrust and torque are obtained for each T_k moment using assignment (9):

$$Tt_k = TT(V_k, N_k); \quad Qq_k = QQ(V_k, N_k). \tag{9}$$

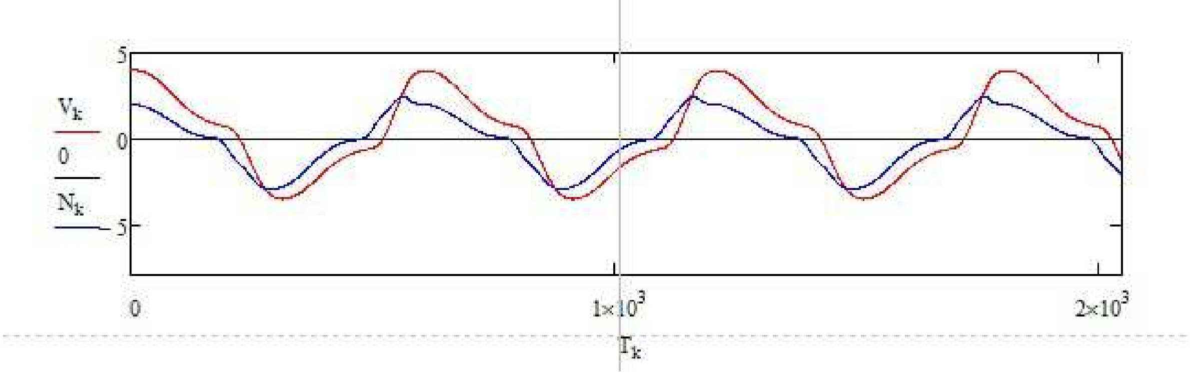

Fig. 5. The temporal variation in the ship's velocity and the screw rotation speed
Рис. 5. Изменение скорости хода судна и оборотов винта во времени

These equations allow represent graphically the other components of the solution. Fig. 6 shows the forces and linear acceleration defined in the first differential equation.

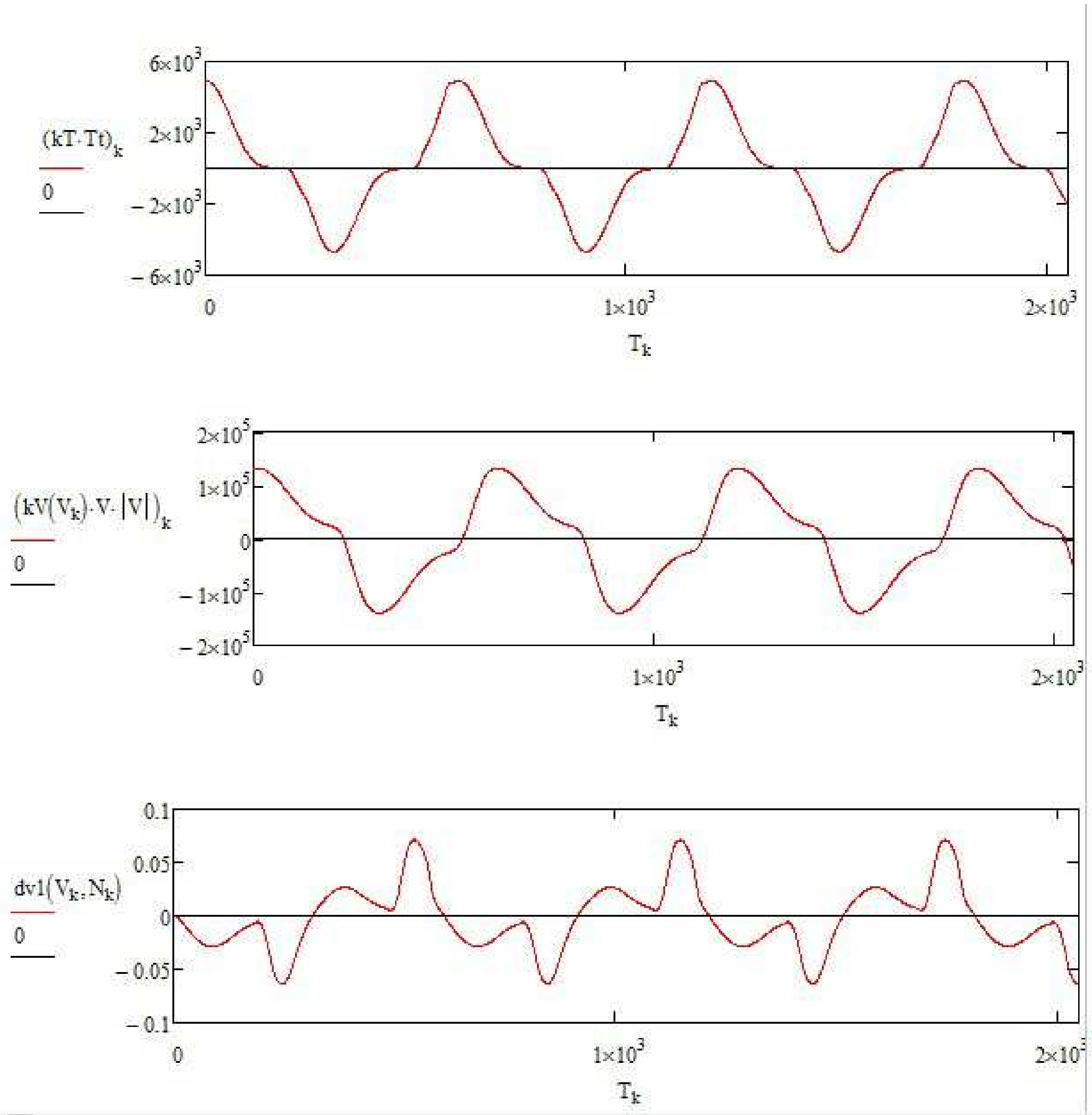

Fig. 6. The temporal variation of the propeller thrust $kT \times Tt$, hydraulic resistance force $kV \times V|V|$, and the ship's linear acceleration dv_1

Рис. 6. Изменение во времени силы тяги винта $kT \times Tt$, сопротивления водной среды $kV \times V|V|$ и линейного ускорения судна dv_1

In Fig. 7, there are moments and angular acceleration in the second differential equation. Fig. 8 completes the graphic series, where the time variation of the angle β is presented, the angle defines the introduction of the screw action coefficients to the curves.

The paralysis mode

The qualitative analysis of these graphs (Fig. 7) demonstrates that all the parameters of the obtained solution change cyclically with the period T_0 = 1 200 s. The most interesting ones are linear and angular accelerations, especially the latter. The last graph in Fig. 7 shows very peculiar changes in some time intervals. For a more detailed study of the accelerations, they are shown in Fig. 10 for the time range 380–920 s, further on this behavior is repeated cyclically. This is the range of time when there is the transition of the screw action coefficients through zero values: at these moments the screw works in paralysis mode, its operation is unstable. It is clear that the linear acceleration dv_1 changes less abruptly than the angular acceleration dn_1. The exact position of the paralysis modes is easy to determine using the graphs in Fig. 3.

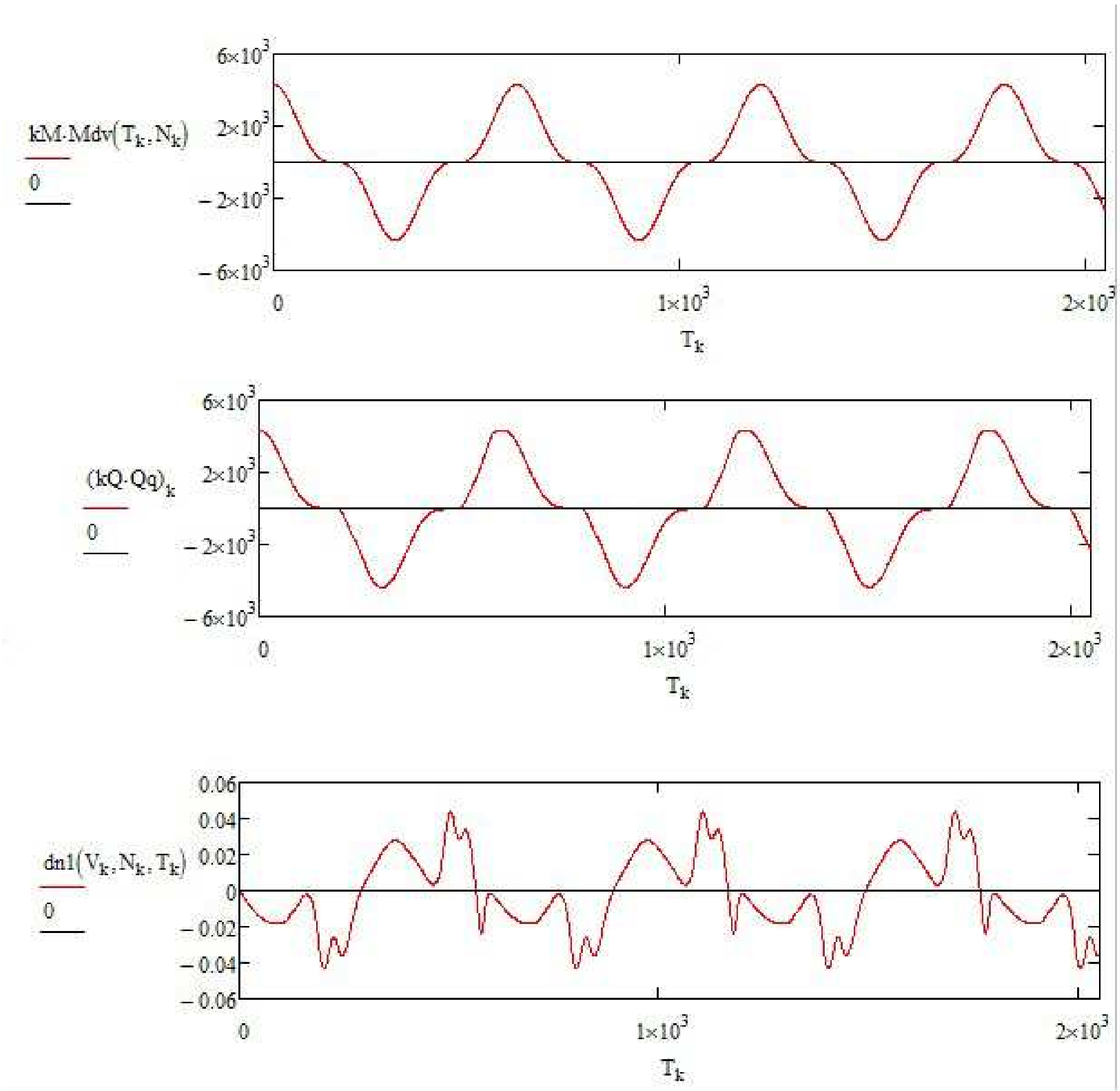

Fig. 7. The temporal variation of the engine torque $kM \times Mdv$, the screw torque $kQ \times Qq$, and the angular acceleration dn_1

Рис. 7. Изменение во времени момента двигателя $kM \times Mdv$, момента винта $kQ \times Qq$ и углового ускорения винта dn_1

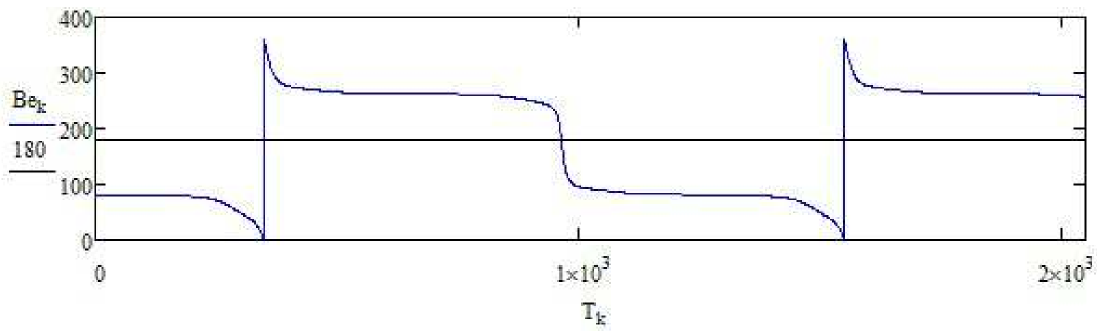

Fig. 8. The temporal variation of the screw blade inflow angle β(*Be*)

Рис. 8. Изменение во времени угла β(*Be*) набегания потока на лопасть винта

The two positions on these graphs (where the curves almost simultaneously cross the abscissa axis) are found by tracing which defines the left point of the paralysis mode $\beta_1 = 112°$ (transition from ahead to reverse) and the right point $\beta_2 = 292°$ (transition from reverse to ahead). Having found these coordinates, it is possible to refer to Fig. 9, where the two values of the angles β_1 and β_2 reveal the moments of time when they are reached: $T_1 = 796$ s and $T_2 = 1\,573$ s. Therefore, we display the graphics of Fig. 10 in the range with a margin including

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these moments of time, namely: 880–1 780 s. They clearly demonstrate the behavior of accelerations in the zone of the paralysis modes.

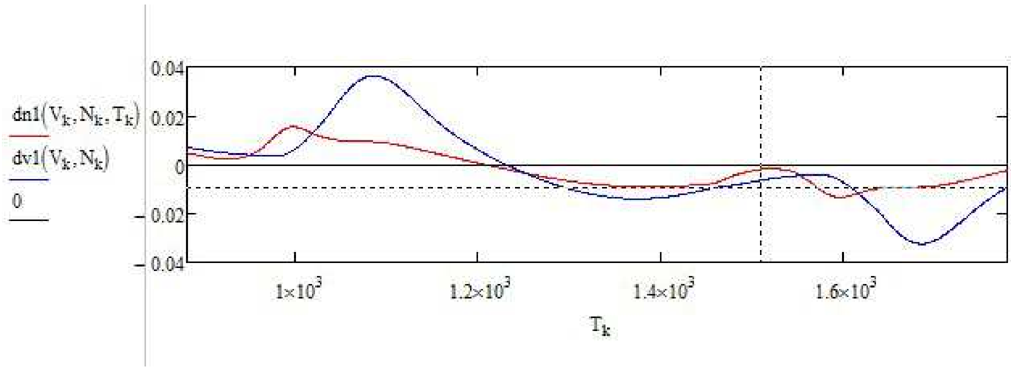

Fig. 9. The linear acceleration of the ship and the angular acceleration of the screw in the interval 380–920 s (the paralysis mode)
Рис. 9. Ускорения: линейное судна и угловое винта в интервале времени 380–920 с (паральный режим)

Results and discussions

The answer to the question whether the paralysis mode generates oscillations with higher frequencies than the base frequency f_0 of the engine torque change (here it is equal to $f_0 = 1 / 1\,200$ s) seems to be the most notable one. For this purpose, the fast Fourier transform has been performed using the built-in function *fft*() included in MathCad. We have applied it to the vessel's velocity *v*, and to the linear acceleration of the vessel and the angular one of the propeller:

$$Vf = fft(V); \quad DVf = fft(dv1); \quad DNf = fft(dn1). \tag{10}$$

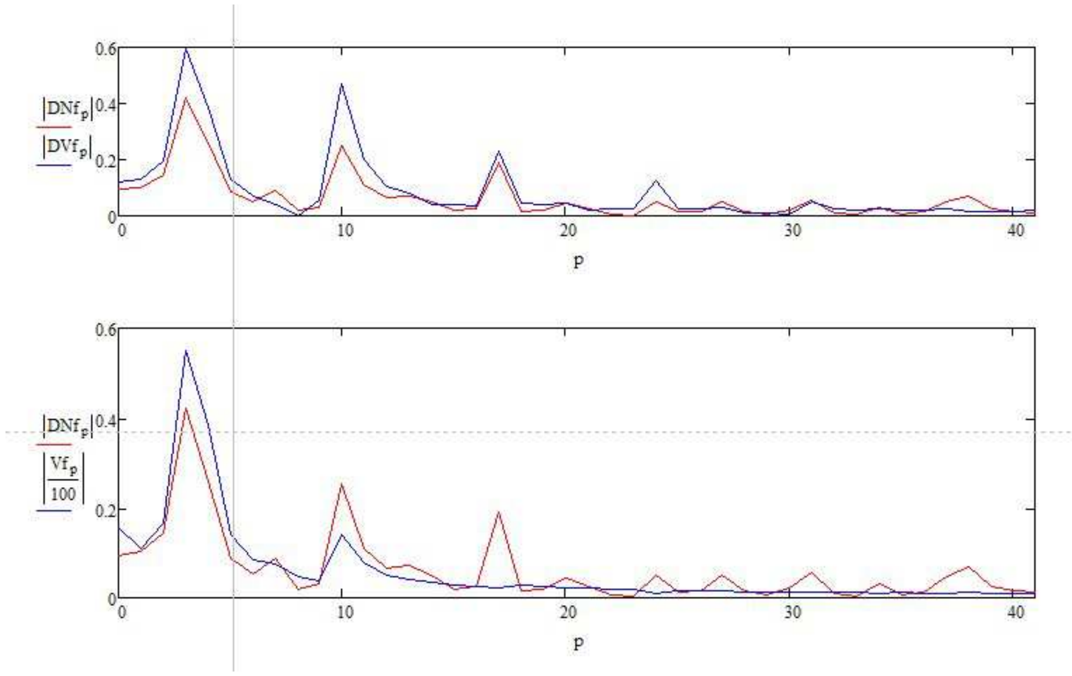

Fig. 10. The spectra of the ship's velocity, accelerations of the linear ship and angular screw
Рис. 10. Спектры скорости хода, ускорений линейного судна и углового винта

The obtained spectra are represented by the curves in Fig. 10. The upper graph of the figure reveals that the both accelerations have almost the same frequency composition, i. e. the paralysis mode does not lead to a special behavior of the screw revolutions. In the graph, three harmonics – multiples of the base frequency: $10\times f_0$, $17\times f_0$ and $24\times f_0$ – can be noted as significant. The fact is that the high frequencies occur, but they are found both in linear and angular accelerations. The bottom graph of Fig. 10 presents the spectrum of the angular acceleration *DNf* and spectrum *Vf* of the vessel velocity to be compared. It clearly shows that the velocity spectrum has only two harmonics – base and 10-fold. At the same time, the angular acceleration has a number of harmonics of small amplitudes, where speed fluctuations are practically absent.

The simulation of cyclic reversing movements shows that it can be used for simulating any rectilinear maneuvers of the vessel (i. e. without using the rudder). It is sufficient to change the function of the statutory revolutions (the second line in Fig. 5). Let us change it to function:

$$nUst(t) := \left| \begin{array}{l} nU \leftarrow n0 - 2n0 \cdot \cos\left(\dfrac{2\pi t}{T0}\right) \\ kv \leftarrow n0 \quad if \;\; nU > 0 \\ nU \leftarrow -n0 \quad otherwise \\ \; return \;\; nU \end{array} \right. . \tag{11}$$

This means that the statutory revolutions of ahead and reverse speed n_0 are maintained for some time. In this case the conduct of the screw rotation speed and vessel velocity will have the graph shown in Fig. 11. Thus, a mere restatement of the function of the statutory revolutions $nUst(t)$ allows to solve completely new tasks of modelling rectilinear maneuvers. This particular method is used in the VB6 maneuvering simulator programme for creating an interface control of the vessel's movement, Fig. 12 (similar to the engine order telegraph). Moving the vertical slider on the right side by means of the mouse actually changes the statutory revolutions, and the control system switches to them at the real time rate. The change is indicated by darkening the vertical bar next to the slider.

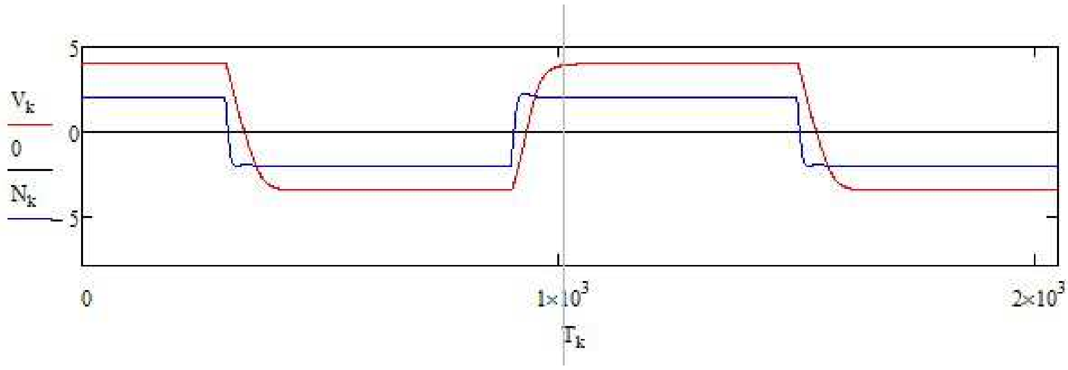

Fig. 11. The change of ship's velocity due to the change of statutory revolutions from (5) to (11)
Рис. 11. Изменение скорости хода и оборотов винта при смене функции уставных оборотов с (5) на (11)

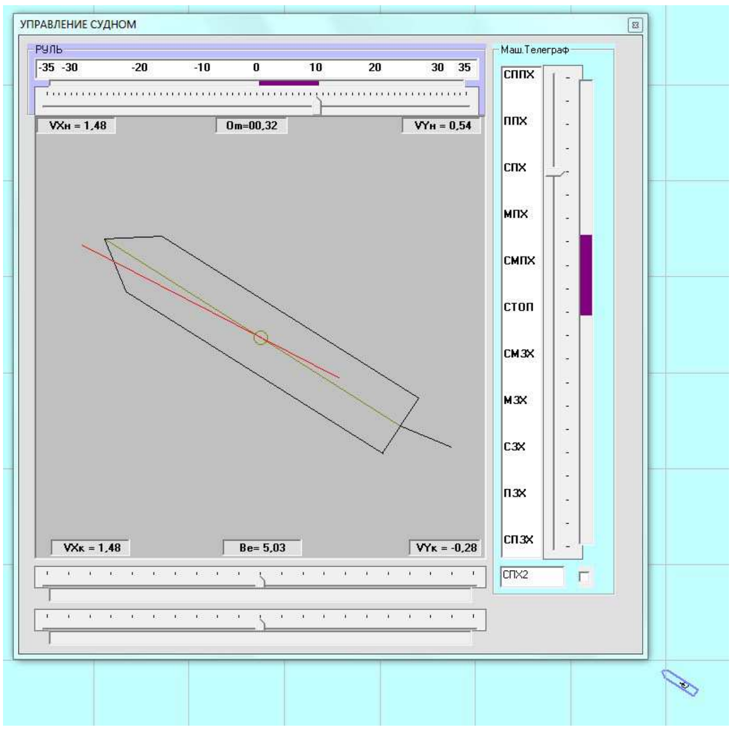

Fig. 12. The control interface of the maneuvering in the VB6 simulator programme
Рис. 12. Интерфейс управления ходами судна в тренажерной программе маневрирования (VB6)

In this case, the slider (engine order telegraph) is set on Half Ahead, the speed has not yet reached the specified set point. The other controls (the rudder and maneuvering device) are not associated with the moves. After moving the slider, the system of the differential equations' integration (mentioned above) operates. Here ahead and astern direction of the vessel can be arbitrarily changed as necessary in such maneuvers. The ship, which is operated, is located in the lower right corner of the water area. After the closure of the control we see the full trajectory of the vessel in the water area.

Conclusions

The above solutions and results presented in the numerical and graphical forms allow us to draw the following conclusions.

1. The modified curves of the screw action correctly reflect the results in all quadrants of the screw blade inflow angle.

2. The problem with the cyclic reverse vessel movement, typical of maneuvering, for example, while hose-mooring at the oil terminal, is simply solved with the help of these curves.

3. These curves can also be used in solving maneuvering problems with an arbitrary change in the engine speed.

4. The considered approach to modelling is easily implemented in the interface maneuver control of computer simulators.

5. MathCad provides convenient built-in tools for solving similar research problems, but the interface control tool has to be created in a different programming environment (C++, VB6).

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Моделирование циклических реверсивных движений судна с использованием модифицированных кривых действия винта Ламмерена

В отечественной практике традиционно используются кривые действия винта либо для положительных значений оборотов винта n и скорости хода судна v, либо когда одна из этих характеристик движения отрицательна. Следовательно, те кривые действия винта, которые мы используем, не позволяют создавать компьютерные тренажеры для отработки специфических задач маневрирования с реверсивными ходами. Цель работы состоит в исследовании возможностей математического моделирования реверсивных движений судна, при которых постоянно изменяется поступь винта фиксированного шага. В зарубежных источниках фигурируют универсальные кривые действия винта Ламмерена. Специфика этих кривых состоит в том, что входом в них является не сама поступь винта, а угол β направления, набегающего на лопасть винта потока. Данный угол определяется через тангенс $tg(\beta) = v/(0,7\pi nD)$, он "чувствителен" к изменению знака как скорости v, так и оборотов n. Поэтому такие кривые действия винта выстроены как функции угла β в диапазоне углов 0–360°. Кривые получены и описаны Ламмереном как результаты обработки опытных модельных данных по коэффициентам упора и момента винта и аппроксимированы рядами Фурье, в которых оставлено по 20 членов. Этими кривыми действительно можно пользоваться как универсальными, что позволяет средствами пакета MathCad проинтегрировать систему двух уравнений – движения судна и вращения винта с произвольными знаками направления этих движений. Задавая закон регулирования оборотов судового двигателя, можно смоделировать произвольные маневры судна с любой сменой направлений движения. Рассмотренный подход к моделированию проверен в настоящей статье и реализован в интерфейсном органе управления маневрированием судна в рамках компьютерного тренажера.

Ключевые слова: реверс движителя, математическое моделирование, кривые действия винта, диаграмма Ламмерена.