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Coordinate separation method for modeling the ship winch drive

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Abstract. The operation of the lifting equipment of a fishing vessel has a number of differences from similar shore devices or cranes and winches operated on transport vessels. The difference from coastal equipment is the external impact from the marine environment, manifested by on-board or keel rolling. The lifting equipment of a transport vessel, influenced by hydrometeorological factors, transports cargo with constant parameters, i.e. the effective load can be calculated according to a proven methodology in accordance with standards. The relevance of the task of improving the methodology for calculating operational loads acting on the lifting equipment of a fishing vessel is confirmed. The accuracy of mathematical models plays a key role in the development of an automatic control system, which must be taken into account when designing modern fishing vessels. When developing mathematical models, both hydrometeorological factors (wind and wave load, surface and underwater current) and variable parameters of the towed object (mass, hydrodynamic resistance, shape, movement on the ground, etc.) should be considered. Forecasting the dynamic behavior of each element of the "ship - winch - cable - towed object" system it will ensure operational and environmental safety, reliability, as well as energy and economic efficiency of the new fishing vessel as a whole. The method of coordinate separation used for mathematical modeling of the ship's winch drive, the operation of which is characterized by non-stationary dynamic processes arising from the effects of hydrometeorological factors and variable loading from the towed object, is presented. The advantage of this modeling method is the choice of any coordinate as an independent one, without being tied to the actual location.

Keywords: winch, towed object, dynamic loads, coordinate separation, mathematical model

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Научная статья

Метод координатного разделения при моделировании привода судовой лебедки

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Аннотация. Работа грузоподъемного оборудования рыбопромыслового судна имеет ряд отличий от подобного рода береговых устройств или кранов и лебедок, эксплуатирующихся на транспортных судах. Отличием от берегового оборудования является внешнее воздействие от морской среды, проявляющееся бортовой или килевой качкой. Грузоподъемное оборудование транспортного судна, испытывая влияние гидрометеорологических факторов, осуществляет транспортировку груза с постоянными параметрами, т. е. действующую нагрузку можно рассчитать по апробированной методике в соответствии со стандартами. Подтверждается актуальность задачи совершенствования методики расчета эксплуатационных нагрузок, действующих на грузоподъемное оборудование рыбопромыслового судна. Точность математических моделей играет ключевую роль при разработке системы автоматического управления, что необходимо учитывать при проектировании современных рыбопромысловых судов. При разработке математических моделей следует предусматривать как гидрометеорологические факторы (ветровая и волновая нагрузка, поверхностное и подводное течение), так и переменные параметры буксируемого объекта (масса, гидродинамическое сопротивление, форма, движение по грунту и т. д.). Прогнозирование динамического поведения каждого элемента системы «судно – лебедка – трос – буксируемый объект» позволит обеспечить эксплуатационную и экологическую безопасность, надежность, а также энергетическую и экономическую эффективность нового рыбопромыслового судна в целом. Представлен метод координатного разделения, используемый для математического моделирования привода судовой лебедки, работа которой отличается нестационарными динамическими процессами, возникающими из-за воздействия гидрометеорологических факторов и переменного нагружения со стороны буксируемого объекта. Преимуществом такого метода моделирования является выбор в качестве независимой любой координаты, не привязываясь к действительному перемещению.

Ключевые слова: лебедка, буксируемый объект, динамические нагрузки, координатное разделение, математическая модель

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Introduction

The fishing fleet operating in the Azov-Black Sea basin requires global updating. The average age of vessels is more than 25 years. Under the circumstances, the issue of import substitution of ship equipment is becoming topical. The ship winch drive, as a ship auxiliary mechanism, has an impact on the reliability, safety and energy efficiency of the power plant and the ship as a whole. It is therefore particularly important to take into account the dynamic loads on the vessel winch on the side of the towed and lifted object. In particular, such non-stationary dynamic loads can be seen in the trawl winch of a fishing vessel. During trawl fishing, both hydrometeorological factors and variable loads may affect the winch. This can lead to stopping, failure of the drive of the lifting machine, overloading of the main and auxiliary engines, loss of stability of the vessel [1-3]. Therefore, when creating an automated control system for a trawl complex that directly affects the energy efficiency of the ship, it is necessary to predict the behavior of the elements of the winch drive. Existing mathematical models describing the dynamics of ship winches do not take into account non-stationary processes and variable loading of the towed object, which is necessary in the automation of the process [4-7]. Hence, the search for adequate models is an urgent task caused by the demands of practice.

Research materials and methods

The aim of the work is to build a mathematical model of movement of the system "ship - winch - rope - towed object" (Fig. 1).

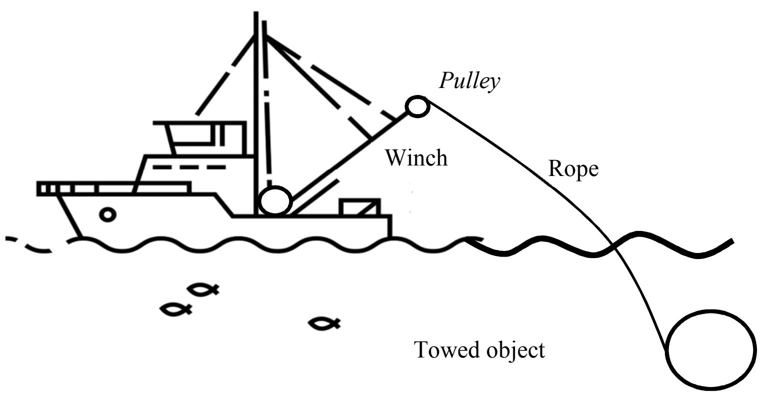

Fig. 1. System "ship - winch - rope - towed object"

The trawl winch consists of three solid bodies (Fig. 2). The solid body *1* is a rolling drum, which is a link with a hinge-fixed support, the solid body *2* - a rope from the drum to the pulley, which is also considered to be a fixed link, the solid body *4* - a towable object (TO) moving on the ground, the center of which is at point B. The movement of the solid body *4* is transmitted by the tension of the cable *3*. By rotating the drum *1* with a given angular speed, the TO *4* will make a straight-line movement. Pulley movement in this case will not be taken into account.

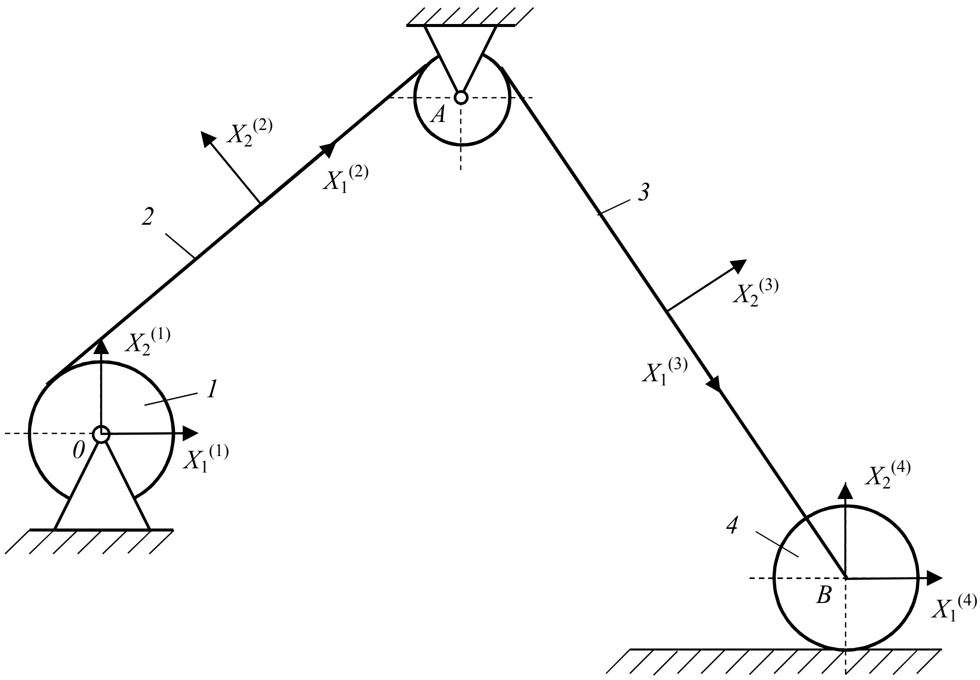

Fig. 2. Structural diagram of a trawl winch

In order to study the movement of this mechanism in the Cartesian coordinates, we will select a coordinate system for each solid body [8-11]. The centers of these local coordinate systems are assumed to be rigidly connected to the geometric center of the corresponding solid bodies.

Therefore, we define the Cartesian coordinates of the bodies (links) as follows in accordance with the Shaban method:

$$\mathbf{q}_k^{(1)} = \left[R_1^{(1)} \quad R_2^{(1)} \quad \theta^{(1)} \right]^{\mathrm{T}};$$

$$\mathbf{q}_k^{(2)} = \left[R_1^{(2)} \quad R_2^{(2)} \quad \theta^{(2)} \right]^{\mathrm{T}};$$

$$\mathbf{q}_k^{(3)} = \left[R_1^{(3)} \quad R_2^{(3)} \quad \theta^{(3)} \right]^{\mathrm{T}};$$

$$\mathbf{q}_k^{(4)} = \left[R_1^{(4)} \quad R_2^{(4)} \quad \theta^{(4)} \right]^{\mathrm{T}},$$

where $R_1^{(i)}$ and $R_2^{(i)}$ are coordinates of the origin of the coordinate system $X_1^{(i)}X_2^{(i)}$ of the i-th solid body, defined relative to the base coordinate system; $\theta^{(i)}$ – angular orientation of the i-th solid body. Thus, the system vector **q** in Cartesian coordinates is defined as

$$\mathbf{q} = \left[q_1 \quad q_2 \quad q_3 \quad \cdots \quad q_{12} \right]^{\mathrm{T}} = \left[\mathbf{q}_k^{(1)\mathrm{T}} \quad \mathbf{q}_k^{(2)\mathrm{T}} \quad \mathbf{q}_k^{(3)\mathrm{T}} \quad \mathbf{q}_k^{(4)\mathrm{T}} \right]^{\mathrm{T}} =$$

$$= \left[R_1^{(1)} \quad R_2^{(1)} \quad \theta^{(1)} \quad R_1^{(2)} \quad R_2^{(2)} \quad \theta^{(2)} \quad R_1^{(3)} \quad R_2^{(3)} \quad \theta^{(3)} \quad R_1^{(4)} \quad R_2^{(4)} \quad \theta^{(4)} \right]^{\mathrm{T}}.$$

However, these coordinates are not independent because of kinematic limitations on the movement of the mechanism elements. These limitations can be defined as follows. The solid body *1* is a fixed link, i.e.

$$R_1^{(1)} = 0;\ R_2^{(1)} = 0;\ \theta^{(1)} = 0.$$

These restrictions are basic. The position of the geometric center of the rope element *2* is relative to the center of the drum *1* - the point *O* in the system $X_1^{(1)} X_2^{(1)}$ can be defined as

$$\mathbf{R}^{(2)} + \mathbf{A}^{(2)} = \bar{\mathbf{u}}_0^{(2)},$$

where $\mathbf{R}^{(2)} = [R_1^{(2)}\ R_2^{(2)}]^{\mathrm{T}}$; $\mathbf{A}^{(2)}$ – a matrix of transformation from the local coordinate system of the solid body *2* to the base coordinate system; $\bar{\mathbf{u}}_0^{(2)}$ – a vector of the position of the point *O* in the coordinate system of the rope 2, i.e.

$$\bar{\mathbf{u}}_0^{(2)} = \begin{bmatrix} -\dfrac{l^{(2)}}{2} & 0 \end{bmatrix}^{\mathrm{T}},$$

where $l^{(2)}$ – a rope length *2*.

The cable element *2* is connected to the cable element *3* through the pulley *A*. Denoting the length of the cable element *3* through $l^{(3)}$, we will write down the position of the cable elements *2* and *3* in the Cartesian coordinates as

$$\mathbf{R}^{(2)} + \mathbf{A}^{(2)}\bar{\mathbf{u}}_A^{(2)} - \mathbf{R}^{(3)} - \mathbf{A}^{(3)}\bar{\mathbf{u}}_A^{(3)} = 0,$$

where $\mathbf{R}^{(i)} = [R_1^{(i)}\ \ R_2^{(i)}]^{\mathrm{T}}$; $\mathbf{A}^{(i)}$ – a matrix of transformation from the local coordinate system of the solid body i to the base coordinate system; $\bar{\mathbf{u}}_A^{(i)}(i = 2.3)$ – the local position of the body in the connection, in this case they have the form

$$\bar{\mathbf{u}}_A^{(2)} = \begin{bmatrix} \dfrac{l^{(2)}}{2} & 0 \end{bmatrix}^{\mathrm{T}};$$

$$\bar{\mathbf{u}}_A^{(3)} = \begin{bmatrix} -\dfrac{l^{(3)}}{2} & 0 \end{bmatrix}^{\mathrm{T}}.$$

The connection of bodies *3* (a section of a cable of variable length) and *4* (a towable object) is assumed to be hinged at a point *B*. Therefore, let's write the connection between these bodies as

$$\mathbf{R}^{(3)} + \mathbf{A}^{(3)}\bar{\mathbf{u}}_B^{(3)} - \mathbf{R}^{(4)} - \mathbf{A}^{(4)}\bar{\mathbf{u}}_B^{(4)} = 0,$$

in which

$$\bar{\mathbf{u}}_B^{(3)} = \begin{bmatrix} \dfrac{l^{(3)}}{2} & 0 \end{bmatrix}^{\mathrm{T}}, \quad \bar{\mathbf{u}}_A^{(4)} = \begin{bmatrix} 0 & 0 \end{bmatrix}^{\mathrm{T}}.$$

Movement of the towed object *4* should meet the following kinematic restriction

$$R_2^{(4)} = 0;\ \theta^{(4)} = 0.$$

The results of the research and discussion

The mechanical system that is being discussed, which is known as a "winch - rope - towed object", includes 12 Cartesian coordinates and 11 algebraic equations. These equations can be rephrased as follows: 3 basic restrictions, 2 restrictions that fix the coordinates of the *O* point, 4 restrictions that describe the mobile connections at points *A* and *B* and 2 restrictions describing the movement of the towed object [12-14]. That is, the studied system has one degree of freedom. Then, taking a virtual change of generalized coordinates of the system, the basic limitations

$$\delta R_1^{(1)} = 0;\ \delta R_2^{(1)} = 0;\ \delta\theta^{(1)} = 0.$$

Write down in a matrix form

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \delta R_1^{(1)} \\ \delta R_2^{(1)} \\ \delta\theta^{(1)} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}.$$

Restrictions on the base position of the point *O* are

$$\delta\mathbf{R}^{(2)} + \mathbf{A}_\theta^{(2)}\bar{\mathbf{u}}_0^{(2)} - \delta\theta^{(2)} = 0,$$

where $\mathbf{A}_\theta^{(2)}$ – partial derivative of the flat conversion $\mathbf{A}^{(2)}$ on $\theta^{(2)}$. Using the definition $\bar{\mathbf{u}}_0^{(2)}$, write down the above equation as

$$\begin{bmatrix} 1 & 0 & \dfrac{l^{(2)}}{2}\sin\theta^{(2)} \\ 0 & 1 & -\dfrac{l^{(2)}}{2}\cos\theta^{(2)} \end{bmatrix} \begin{bmatrix} \delta R_1^{(2)} \\ \delta R_2^{(2)} \\ \delta\theta^{(2)} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}.$$

Rotation of the drum relative to the center *A* is obtained in the form of

$$\begin{bmatrix} 1 & 0 & -\dfrac{l^{(2)}}{2}\sin\theta^{(2)} \\ 0 & 1 & \dfrac{l^{(2)}}{2}\cos\theta^{(2)} \end{bmatrix} \begin{bmatrix} \delta R_1^{(2)} \\ \delta R_2^{(2)} \\ \delta\theta^{(2)} \end{bmatrix} - \begin{bmatrix} 1 & 0 & \dfrac{l^{(3)}}{2}\sin\theta^{(3)} \\ 0 & 1 & -\dfrac{l^{(3)}}{2}\cos\theta^{(3)} \end{bmatrix} \begin{bmatrix} \delta R_1^{(3)} \\ \delta R_2^{(3)} \\ \delta\theta^{(3)} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix};$$

or

$$\begin{bmatrix} 1 & 0 & -\dfrac{l^{(2)}}{2}\sin\theta^{(2)} & -1 & 0 & -\dfrac{l^{(3)}}{2}\sin\theta^{(3)} \\ 0 & 1 & \dfrac{l^{(2)}}{2}\cos\theta^{(2)} & 0 & -1 & \dfrac{l^{(3)}}{2}\cos\theta^{(3)} \end{bmatrix} \begin{bmatrix} \delta R_1^{(2)} \\ \delta R_2^{(2)} \\ \delta\theta^{(2)} \\ \delta R_1^{(3)} \\ \delta R_2^{(3)} \\ \delta\theta^{(3)} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}.$$

For rotational connection at the point *B* we have

$$\begin{bmatrix} 1 & 0 & -\frac{l^{(3)}}{2}\sin\theta^{(3)} & -1 & 0 & 0 \\ 0 & 1 & \frac{l^{(3)}}{2}\cos\theta^{(3)} & 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} \delta R_1^{(3)} \\ \delta R_2^{(3)} \\ \delta\theta^{(3)} \\ \delta R_1^{(4)} \\ \delta R_2^{(4)} \\ \delta\theta^{(4)} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}.$$

Restriction of movement of towed object at the point *B* is provided by the expression

$$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \delta R_2^{(4)} \\ \delta\theta^{(4)} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

or

$$\begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \delta R_1^{(4)} \\ \delta R_2^{(4)} \\ \delta\theta^{(4)} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}.$$

By combining both equations, we will have

$$\mathbf{C_q}\delta\mathbf{q} = 0,$$

where

$$\mathbf{q} = \begin{bmatrix} R_1^{(1)} & R_2^{(1)} & \theta^{(1)} & R_1^{(2)} & R_2^{(2)} & \theta^{(2)} & R_1^{(3)} & R_2^{(3)} & \theta^{(3)} & R_1^{(4)} & R_2^{(4)} & \theta^{(4)} \end{bmatrix}^{\mathrm{T}}$$

and $\mathbf{C_q}$ – Jacobi matrix of dimension 11×12, which can be written as

$$\mathbf{C_q} = [C_{i,j}],$$

where non-zero elements are defined as

$$C_{1,1} = C_{2,2} = C_{3,3} = C_{4,4} = C_{5,5} = C_{6,4} = C_{7,5} = C_{8,7} = C_{9,8} = C_{10,11} = C_{11,12} = 1;$$

$$C_{6,7} = C_{7,8} = C_{8,10} = C_{9,11} = -1;$$

$$C_{4,6} = \frac{l^{(2)}}{2}\sin\theta^{(2)}; \quad C_{5,6} = -\frac{l^{(2)}}{2}\cos\theta^{(2)}; \quad C_{6,6} = -\frac{l^{(2)}}{2}\sin\theta^{(2)};$$

$$C_{7,6} = \frac{l^{(2)}}{2}\cos\theta^{(2)}; \quad C_{6,9} = -\frac{l^{(3)}}{2}\sin\theta^{(3)}; \quad C_{7,9} = \frac{l^{3}}{2}\cos\theta^{3};$$

$$C_{8,9} = -\frac{l^{(3)}}{2}\sin\theta^{(3)}; \quad C_{9,9} = \frac{l^{(3)}}{2}\cos\theta^{(3)}.$$

If $\theta^{(2)}$ is chosen as an independent coordinate, then the Jacobi matrix will take the form of

$$\mathbf{C}_{\mathbf{q}d}\delta\mathbf{q}_d + \mathbf{C}_{\mathbf{q}i}\delta\mathbf{q}_i = 0,$$

where $\mathbf{C}_{\mathbf{q}d}$ – Jacobi matrix connected to the dependent coordinates. It's a square matrix, measuring 11×11; $\mathbf{C}_{\mathbf{q}i}$ – Jacobi matrix connected to the independent coordinate $\theta^{(2)}$. In this case $\mathbf{C}_{\mathbf{q}i}$ is an 11-dimensional Vector of dependent and independent coordinates defined as

$$\mathbf{q}_d = \begin{bmatrix} R_1^{(1)} & R_2^{(1)} & \theta^{(1)} & R_1^{(2)} & R_2^{(2)} & R_1^{(3)} & R_2^{(3)} & \theta^{(3)} & R_1^{(4)} & R_2^{(4)} & \theta^{(4)} \end{bmatrix}^{\mathrm{T}};$$

$$\mathbf{q}_i = \theta^{(2)},$$

the Vector $\mathbf{C}_{\mathbf{q}i}$ is defined as

$$\mathbf{C}_{\mathbf{q}i} = \begin{bmatrix} 0 & 0 & 0 & C_{4,6} & C_{5,6} & C_{6,6} & C_{7,6} & 0 & 0 & 0 & 0 \end{bmatrix}^{\mathrm{T}} =$$

$$= \begin{bmatrix} 0 & 0 & 0 & \frac{l^{(2)}}{2}\sin\theta^{(2)} & -\frac{l^{(2)}}{2}\cos\theta^{(2)} & -\frac{l^{(2)}}{2}\sin\theta^{(2)} & \frac{l^{(2)}}{2}\cos\theta^{(2)} & 0 & 0 & 0 & 0 \end{bmatrix}^{\mathrm{T}},$$

and the matrix $\mathbf{C}_{\mathbf{q}d}$ is defined as

$$\mathbf{C}_{\mathbf{q}d} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & C_{6,9} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & -1 & C_{7,9} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & C_{8,9} & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & C_{9,9} & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}.$$

Obviously, $\mathbf{C}_{\mathbf{q}d}$ is a degenerate matrix that can be inverted to write a vector $\delta\mathbf{q}_d$ through a change in the $\delta\theta^{(2)}$ system's degree of freedom as

$$\delta\mathbf{q}_d = -\,\mathbf{C}_{\mathbf{q}d}^{-1}\,\mathbf{C}_{\mathbf{q}i}\,\delta\theta^{(2)}.$$

The peculiarity of this simulation method is that any derivative - the angle of rotation, as in this case, or the movement of the towed object along a horizontal surface - can be chosen as independent $R_1^{(4)}$, i.e. $\mathbf{q}_i = R_1^{(4)}$,

$$\mathbf{q}_d = \begin{bmatrix} R_1^{(1)} & R_2^{(1)} & \theta^{(1)} & R_1^{(2)} & R_2^{(2)} & \theta^{(2)} & R_1^{(3)} & R_2^{(3)} & \theta^{(3)} & R_1^{(4)} & R_2^{(4)} & \theta^{(4)} \end{bmatrix}^{\mathrm{T}}.$$

This means that, using a coordinate partition, it is possible to record the change of a set of $\mathbf{q}_d$ coordinates by changing another set of $\mathbf{q}_i$.

In the case that in a multi-channel system the identification of the matrix $\mathbf{C}_{\mathbf{q}d}$ is difficult due to its nondegeneracy, numerical methods can be used.

Conclusion

The proposed method of generalized coordinate partitioning for mathematical modeling of the system "ship - winch - rope - towed object" can be recommended for formalization of this kind of lifting devices, as independent, you can choose any coordinate without being tied to the actual move. Implementation of the obtained mathematical models is planned to be carried out by means of Python language, using matplotlib, graphical interface DearPyGUI.

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