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SPATIAL NON-STATIONARY MOVEMENT OF A MARINE TETHERED SYSTEM AT MANEUVERING

ПРОСТРАНСТВЕННОЕ НЕСТАЦИОНАРНОЕ ДВИЖЕНИЕ МОРСКИХ ПРИВЯЗНЫХ СИСТЕМ ПРИ МАНЕВРИРОВАНИИ

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Abstract. When designing an underwater towed system (UTS) and selecting possible modes of its movement, of great importance is calculation of the parameters of the towed system (TS) movement at carrier vessel maneuvering. This is caused by the fact that the TS changes its running depth when the vessel moves with an alternating speed, which leads to the appearance of a considerable number of dynamic components of the tether tension and unstable modes of the TS movement. One of such complex vessel maneuvers is the circulation mode. At circulation, the tension and running depth of the TS may significantly differ from those corresponding to the movement with the same speed at straight course. The article considers non-stationary movement of a marine tethered system (MTS) with flexible connection (FC) illustrated by a UTS. The circulation mode of the UTS with FC is shown as an example of calculation on the basis of the computer model of the dynamics of the MTS with FC.

Keywords: marine tethered system (MTS); flexible connection (FC); underwater towed system (UTS); spatial non-stationary movement; mode of movement; circulation.

Аннотация. Рассмотрен пример нестационарного движения морской привязной системы (МПС), имеющей в своём составе гибкую связь (ГС), на примере ПБС. В качестве расчёта приведен режим циркуляции ПБС с ГС на основе созданной компьютерной модели динамики МПС с ГС.

Ключевые слова: морская привязная система (МПС); гибкая связь (ГС); подводная буксируемая система (ПБС); пространственное нестационарное движение; режим движения; циркуляция.

Анотація. Розглянуто нестаціонарний рух морської прив'язної системи (МПС), що має у своєму складі гнучкий зв'язок (ГЗ), на прикладі підводної буксированої системи (ПБС). Як розрахунок наведено режим циркуляції ПБС із ГЗ на основі створеної комп'ютерної моделі динаміки МПС із ГЗ.

Ключові слова: морська прив'язна система (МПС); гнучкий зв'язок (ГЗ); підводна буксирована система (ПБС); просторовий нестаціонарний рух; режим руху; циркуляція.

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Problem statement. TAs stated in the paper by Yu. E. Shamarin et al. [5, p. 5], the problems of studying nonlinear dynamics of underwater oceanographic systems (UOS) belong to the most complex problems in the mechanics of continual systems. In this case, substantial difficulties arise in the construction of mathematical models. Cable systems are approximated in the range from a rigid rod or spring to a system of twisted wires [6; 14]. Carriers of equipment are compared to miniature aircrafts, dynamics (ballistics) of which is an independent branch of mechanics [1]. It is believed that the UOS should be modeled in its entirety, taking into account the mutual influence of all constituents, as well as nonlinear interaction of various types of oscillations, mechanisms of their agitation [6], and influence of the liquid [4; 12; 15].

Of the variety of possible models, one should choose those that can reliably simulate all the significant processes taking place during the UOS launch and operation. At the same time, they should be fit for effective application with the capabilities of modern computers [5].

Until now, these studies have not been developed due to the lack of reliable mathematical models that are implemented quite simply and effectively in the form of algorithms and programs for the numerical solution of the problems under consideration. According to E. I. Blinov and his coauthors [2], description of the influence of hydro-meteo conditions requires an adequate spatial and temporal mathematical model of the wave, wind and current variation. This model should allow real external conditions to be reproduced in both short (seconds, minutes) and long (up to a year) time intervals, taking into account the probabilistic nature and other basic characteristics of the hydro-meteo conditions. The researchers proposed a description of the numerical method for solving the problem of control of a flexible spatially curved object with directed force impacts. The existing mathematical model of the FC behavior makes it possible to establish its supposed shape, which will allow for determining its stress-strain state.

Latest research and publication analysis

When a vessel moves at an alternating speed, the towed system changes its running depth, which leads to the appearance of a significant number of dynamic components of the tether tension and unstable modes of movement of the towed vehicle (TV). Since towing at a constant speed is regarded as normal operating conditions for most systems, and accelerated movement is a transition from one fixed speed to another, it is very important to know the duration of the transient process associated with the change in the running depth of the TV, particularly, the long-length equipment carrier — LEC [6, p. 153].

At present, calculation of the dynamic parameters become included to the practice of designing the TS, which provides the developer with more insight into the modes of vessel movement required for the effective operation of the equipment.

There has been performed a calculation of the movement parameters of the system “tether – spherical TV” at an instantaneous change in the vessel’s speed. It has shown that the tether tension increases sharply at the initial moment of movement with positive acceleration; then it decreases to the tension appropriate for towing at a newly acquired speed [6, p. 153]. The running depth of the TV is gradually reduced, and after a few minutes, the TV arrives at an equilibrium position equivalent to the new towing speed. As follows from the experimental data [6], nonstationary modes of the TV with a complex carrying surface can substantially differ from those described above by significant angular oscillations of the TV, which in turn lead to the TV depth oscillations along the trajectory, which is characteristic for a TV without a complex carrying surface. The vehicle is characterized with stability in the flow with respect to small disturbances and loses it when the amplitude of disturbances increases.

As noted by Yu. E. Shamarin and his coauthors [5, p. 12], in practice, there is only one possible approach to the solution of the problems of nonlinear dynamics of the UOS. It is a semiempirical account of the influence of the surrounding liquid [4; 6; 14; 15; 8], which is taken to be equivalent to the impact of external loads corresponding to the inertial, viscous and wave properties of the liquid.

To construct an optimal model that allows for an effective analysis of virtually all real-life modes of the UOS, it is advisable to simulate the tether elements by means of discrete thread approximation [6]. Such models were used in the studies performed by J. Dalamber and D. Bernoulli. This approach is quite effective; even D. W. Rayleigh noted that even an incredible assumption that a string oscillates as two rectilinear segments gave a period with an error of less than 10% [6].

The thread approximation provides a great physical illustration, which allows in each specific case to be limited to the baseline number of discrete elements that approximate the thread. Thus, the problem can be solved with the required degree of accuracy. The solution to the problem of studying nonlinear dynamics of a towed system during the operation of the winch accommodating the tether has been reduced to the numerical integration of the system of N ordinary nonlinear differential equations [5, p. 130]. A special feature of this technique is a variable number of rods that approximate the part of the towed system that is in the water. The flexible long-length towed antenna (FLTA) of neutral buoyancy is approximated in the calculation by a constant number of rods.

The movement of towed systems at vessel maneuvers has been studied by V. I. Poddubnyi, Yu. E. Shamarin, D. A. Chernenko, and L. S. Astakhov [6, p. 159–168]. As the authors note, an alternating speed of the vessel movement makes the TS change its running depth, which leads to the appearance of a significant number of dynamic components of the tether tension and unstable modes of movement of the TV. They also note that calculation of the dynamic parameters become included to the practice of designing the TS, which provides the developer with more insight into the modes of vessel movement required for the effective operation of the equipment.

There has been performed a calculation of the movement parameters of the system “tether – spherical TV” at an instantaneous change in the vessel’s speed. It has shown that the tether tension increases sharply at the initial moment of movement with positive acceleration; then it decreases to the tension appropriate for towing at a newly acquired speed [6, p. 159–168]. The running depth of the TV is gradually reduced, and after a few minutes, the TS arrives at an equilibrium position equivalent to the new towing speed.

The results of calculation of the movement parameters of the TS with a LEC about 750 m long (flexible tether (FT) 500 m long, $V = 3$ m/s, $R_0 \approx$ LTS) [6] at the initial moment of the transition from a straight course to circulation show that the LEC reacts to the vessel maneuver with a prominent delay, for some time moving straight even at the maneuvering of the towing carrier vessel. Then the LEC acquires the shape of an element of the spiral that is directed inside the trajectory of the carrier vessel’s movement. In this case, after $W_T/L_{TS} \sim 0.8$, there is practically no TS displacement in the moving coordinate system. In other words, the transition ends here, and the TS moves in the steady circulation mode. The calculation has showed that the time it takes the TS to change the mode is determined by the TS length. To estimate the time of the TS transition to steady circulation, one should use a time interval required for the vessel to cover the distance equal to the TS length. As follows from the experimental data [6], nonstationary modes of the TV with a complex carrying surface can substantially differ from those described above by significant angular oscillations of the TV, which in turn lead to the TV depth oscillations along the trajectory, which is characteristic for a TV without a complex carrying surface [6].

The issues of the marine tethered system dynamics have also been considered in [2; 7; 9; 10; 12; 13; 16].

THE ARTICLE AIM is to consider nonstationary movement of the MTS with FC on the example of the CV circulation and verify the adequacy of the obtained computer model of the dynamics of the MTS FC on practical examples, which would enable obtaining the MTS characteristics necessary for designing the MTS with FC and testing its operation at maneuvering (illustrated by the UOS circulation).

Basic material. Circulation is one of the basic maneuvers of the CV associated with movement to the given area. Steady circulation can be employed as the main mode of operation of search equipment [6, p. 87]. The presence of a TS at the stern of a vessel can affect its controllability, which is usually characterized by the vessel behavior on steady circulation [5]. At circulation, the tension and running depth of the TS may significantly differ from those corresponding to the movement with the same speed at straight course. Therefore, it is important to calculate parameters of the TS equilibrium at steady circulation during the TS design or the selection of possible modes of movement.

When designing a UTS, of great importance is calculation of the parameters of the TS movement at vessel maneuvering. This is caused by the fact that the TS changes its running depth when the vessel moves with an alternating speed, which leads to the appearance of a considerable number of dynamic components of the tether tension and unstable modes of the TS movement. One of such complex vessel maneuvers is the circulation mode. Vessel circulation is defined as the trajectory of the center of gravity of the vessel that was previously heading straight resulting from the rudder shifting to some constant angle, and the vessel’s movement along this trajectory [11, p. 407]. As a rule, vessel circulation is divided into three stages: maneuvering, which implies a rudder shift (when the rudder is deflected on board, this stage lasts for 10–15 seconds); evolution, which is a change of the vessel’s coordinate parameters (drift angle, angular velocity, linear velocity), ending after the vessel’s course angle is changed by 90°; steady circulation, during which the coordinate parameters remain unchanged. The trajectory thus has the form of a regular circle with the diameter D.

Fig. 1 shows a circulating trawler [24]. Let us consider the spatial nonstationary movement of an MTS consisting of a CV, FC, and an underwater vehicle (UV), which was simulated using a computer program based on the developed mathematical model [17; 18] and the algorithm [19]. The calculation is basically testing of the computer program of the model of dynamics of the MTS with FC [20; 21]. In all cases, the UV weight was set to 150 kg, its buoyancy was considered neutral, and the hydrodynamic resistance coefficient was equal to 1 [22]. The initial length of the FC was set equal to 100 m, its diameter equal to 14 mm. Taking into account the condition of neutral buoyancy of the FC, its bulk weight was set equal to 0.15386 kg/m. The FC was considered elastic; the Young's modulus of its material was set equal to $9.55 \cdot 10^8$ Pa. The FC was divided into 20 elements. The normal coefficient of resistance of each FC element was assumed to be 1.8, and the tangential coefficient was taken to be 0.025. The coordinates of the initial position of the UV with respect to the CV were set on the basis of the assumption that the length of the FC having a rectilinear shape would be 100 m. Then, according to a specially developed algorithm, the UV was moved to a given point of space by means of the FC movement modeling. In such a way, the initial shape of the FC for the MTS movement modeling was determined instead of being defined artificially. Simplification of the process of modeling and visualization of the results obtained were achieved through the use of the principle of "impact inversion": the elements of the system were assumed stable, and the water flow ran up at them with a speed equal to the velocity of the CV and opposite in direction.

Let us consider several options of the CV circulation with a UTS, for example, when there is an unexpected threat in the CV course, the course is changed, or the sea bottom is to be studied in a confined water area.

Option 1. The CV moves along a straight line in the direction of the X axis at the speed of 1 m/s (Fig. 2).

The non-self-propelled UV at the initial moment of time $t = 0$ is at the point A with the following coordinates: $X = 70.7$ m, $Y = 50$ m, $Z = 50$ m. For 95 seconds, the UV moves via a special algorithm to the starting point B with the coordinates $X = 0$, $Y = 50$ m, $Z = 50$ m. After that, the UV starts to follow the CV before reaching the steady state. Fig. 3 shows the change in the shape of the FC connecting the CV and the UV during the CV movement projected onto the $X0Y$ and $X0Z$ planes.

Fig. 4 shows the change in the force of the FC tension affecting the CV and the UV, respectively, with a green and purple line.

Fig. 1. Circulation of the trawler M645

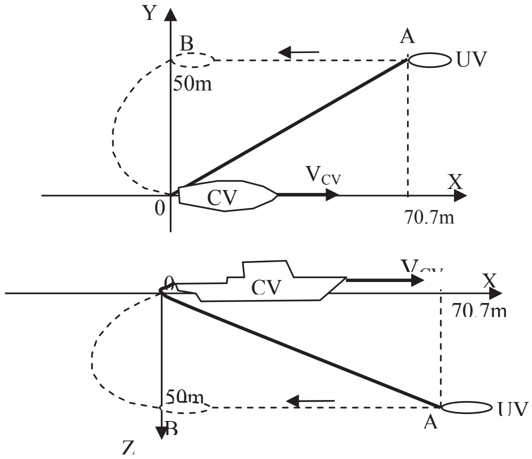

Fig. 2. Pattern of movement of a CV with a TUS

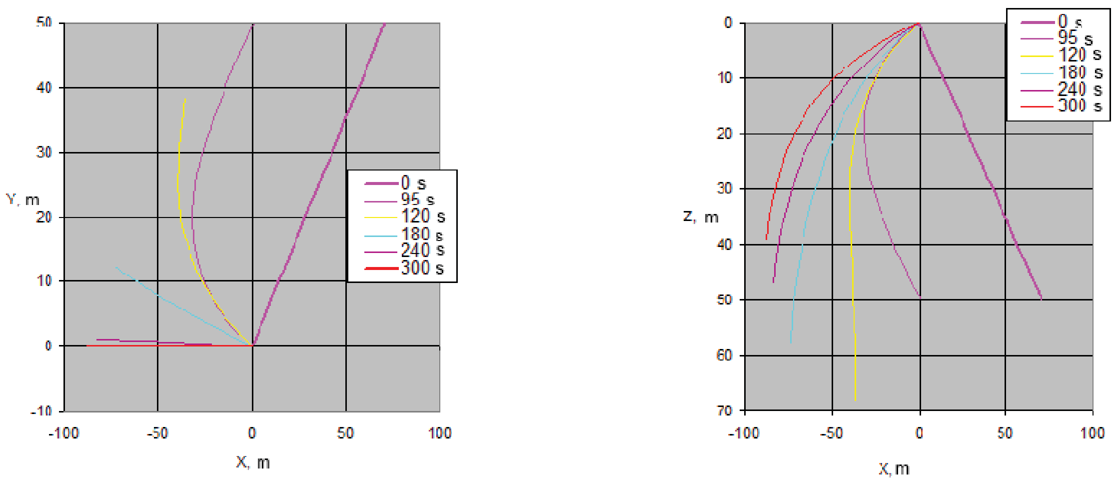

Fig. 3. Change in the shape of the FC connecting the CV and the UV during the CV movement projected onto the *X0Y* and *X0Z* planes

The evolution of the tethered system is completed in 300 seconds with its transition to a steady state. Afterwards, the shape of the FC and the forces acting on the CV and the UV do not change.

Option 2. The CV is static, and the UV moves around it along a circle with the radius of 50 m at the speed of 0.5 m/s at the depth of 50 m, running on its own engine (Fig. 5).

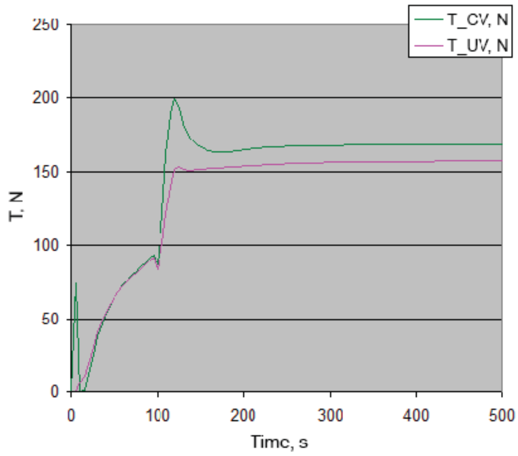

Fig. 4. Change in the force of the FC tension affecting the CV and the UV

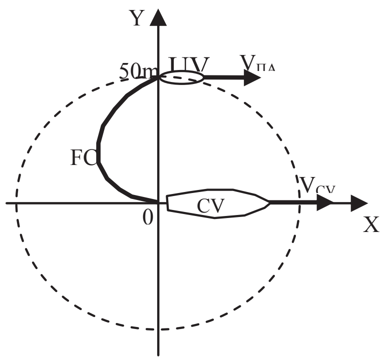

Fig. 5. Scheme of the UV movement around the CV along a circle

Fig. 6 depicts the change in the shape of the FC connecting the CV and the UV during the UV movement projected onto the *X0Y* and *X0Z* planes. The FC lines are indicated by the moments of time at which the FC acquires this shape.

The change in the force of the FC tension acting on the CV and the UV is shown in Fig. 7, respectively, with a green and purple line. In the same figure, the red line references the power of the UV engine at different moments of time. Dividing this power by the engine efficiency of the PA, one can determine its total power.

After transition from point B (Fig. 2), the FC tension and the propulsor power switch to the mode of steady oscillations of a relatively small amplitude caused by the run of transverse and longitudinal waves in the FC (Fig. 7).

Option 3. The CV moves along the *X* axis at the speed of 0.5 m/s, and the UV moves around it along a circle with the radius of 50 m at the same speed and the depth of 50 m using its own engine (Fig. 8).

Fig. 9 depicts the change in the shape of the FC connecting the CV and the UV during the UV movement projected onto the *X0Y* and *X0Z* planes. The FC lines are indicated by the moments of time at which the FC acquires the corresponding shape.

In the absolute coordinate system, the UV moves along a complex loop-like trajectory, so the shape of the FC continuously changes. The change in the force of the FC tension acting on the CV and UV also changes significantly, as shown in Fig. 10, respectively, with green and purple lines.

The red line shows the power of the UV engine at different moments of time. Dividing this power by the

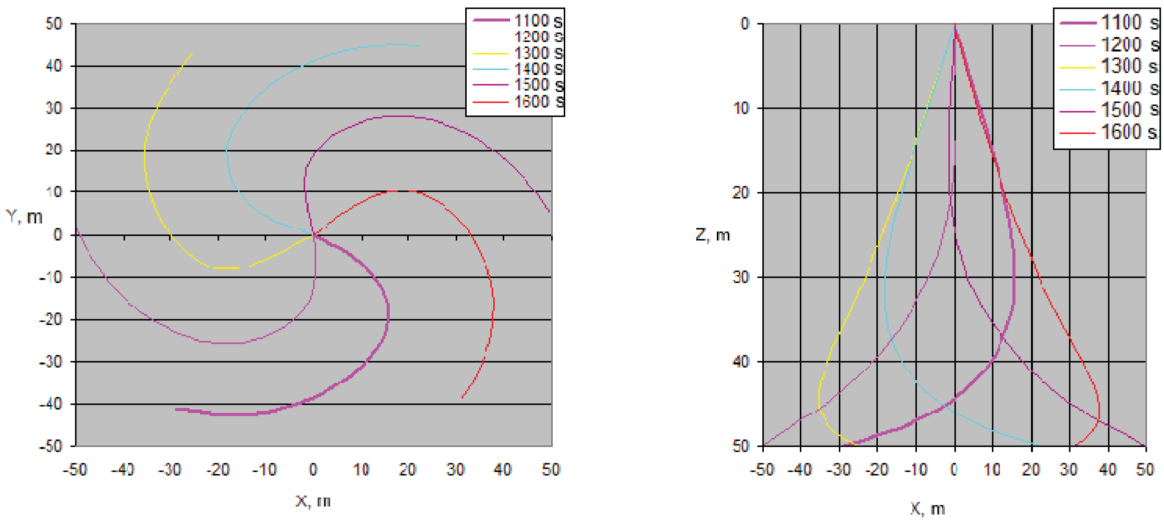

Fig. 6. Change in the shape of the FC connecting the CV and the UV during the UV movement projected onto the *X0Y* and *X0Z* planes

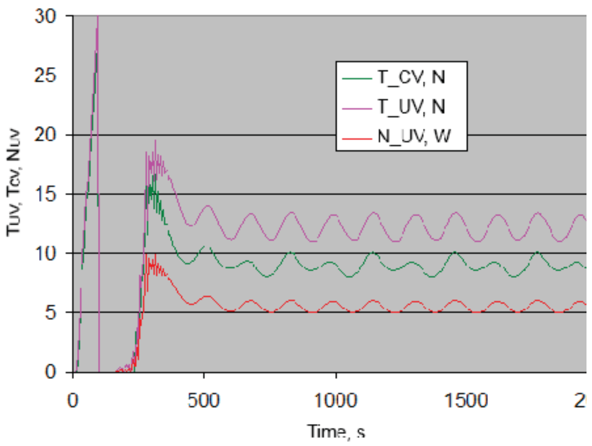

Fig. 7. Change in the force of the FC tension affecting the CV and the UV

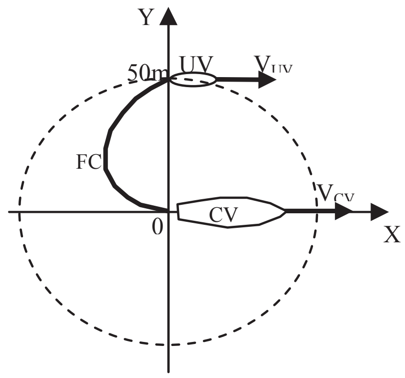

Fig. 8. Scheme of the UV movement around the CV along a circle

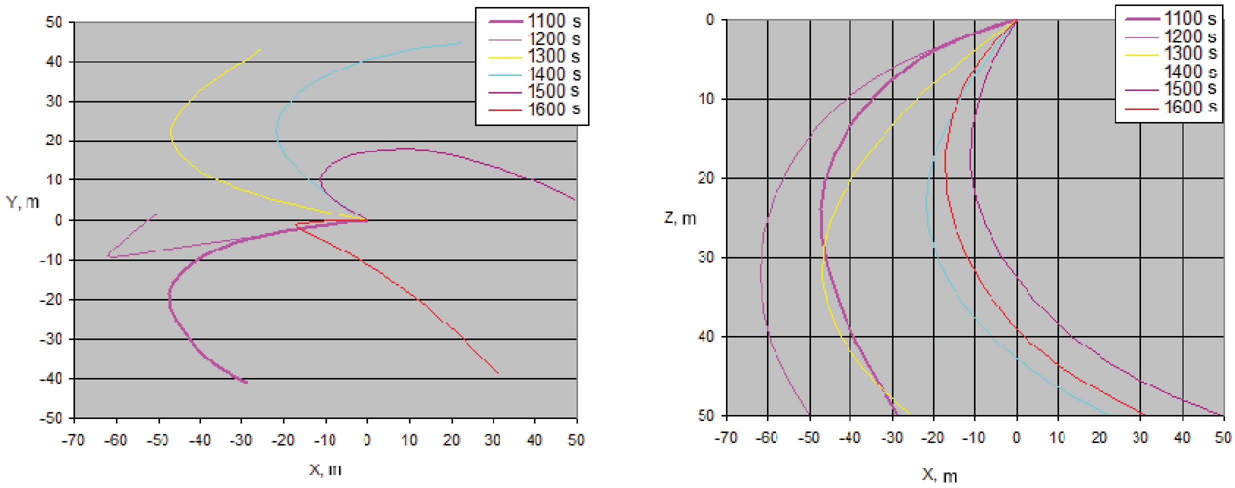

Fig. 9. Change in the shape of the FC connecting the CV and the UV during the UV movement projected onto the *X0Y* and *X0Z* planes

engine efficiency, one can determine its total power. After transition from point B (Fig. 2), the FC tension and the propulsor power switch to the mode of steady oscillations of a large amplitude (compared to Option 2) caused by the run of transverse and longitudinal waves in the FC, as well as the change of the UV movement direction in relation to the CV movement direction (Fig. 10).

Option 3 was taken as a basis for evaluation of the influence of the number of the FC elements on the error in the MTS movement modeling (Fig. 11).

For this purpose, the number of the FC elements was increased from 20 to 30, and the modeling results were compared. They indicate that the shape of the FC remains practically unchanged. The difference between the forces of the FC tension and the propulsor power does not exceed 3 % (Fig. 12).

Option 4 differs from Option 3 by the CV speed. Here, it moves along the *X* axis at the speed of 0.25 m/s. The modeling results are shown in Fig. 13 and 14.

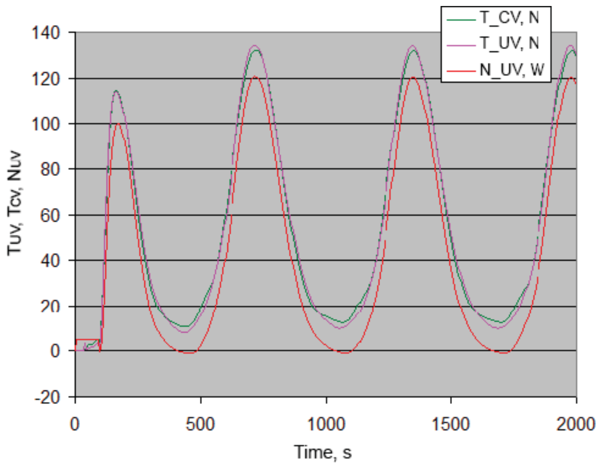

Fig. 10. Change in the force of the FC tension acting on the CV and the UV

Reduction of the UV circulation speed significantly decreases the demand power of the UV propulsor and the force of the FC tension.

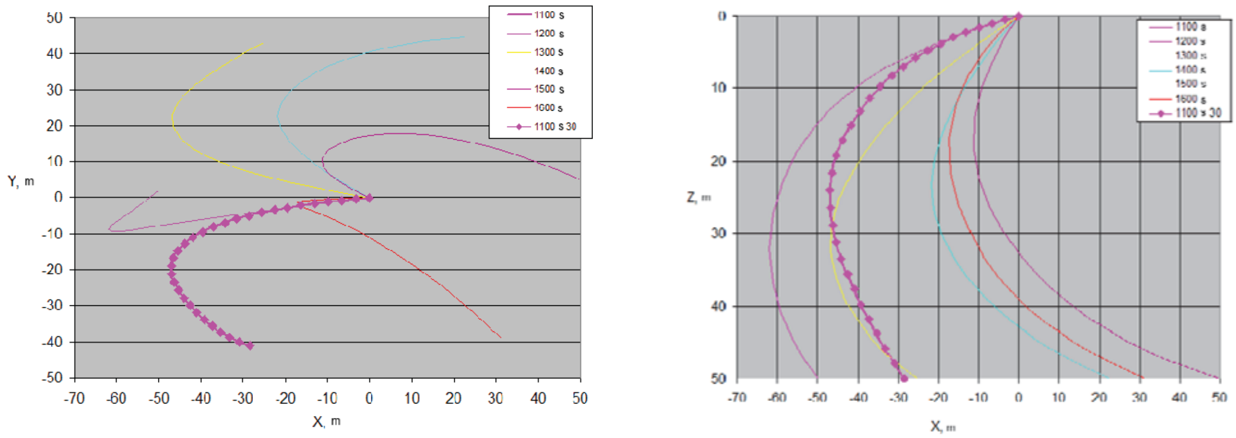

Fig. 11. Evaluation of the influence of the number of the FC elements (increased from 20 to 30) on the error in the MTS movement modeling

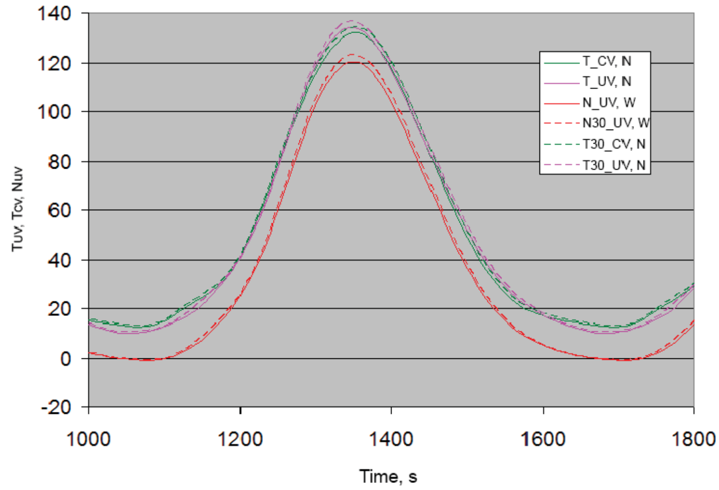

Fig. 12. Difference between the forces of the FC tension and the propulsor power

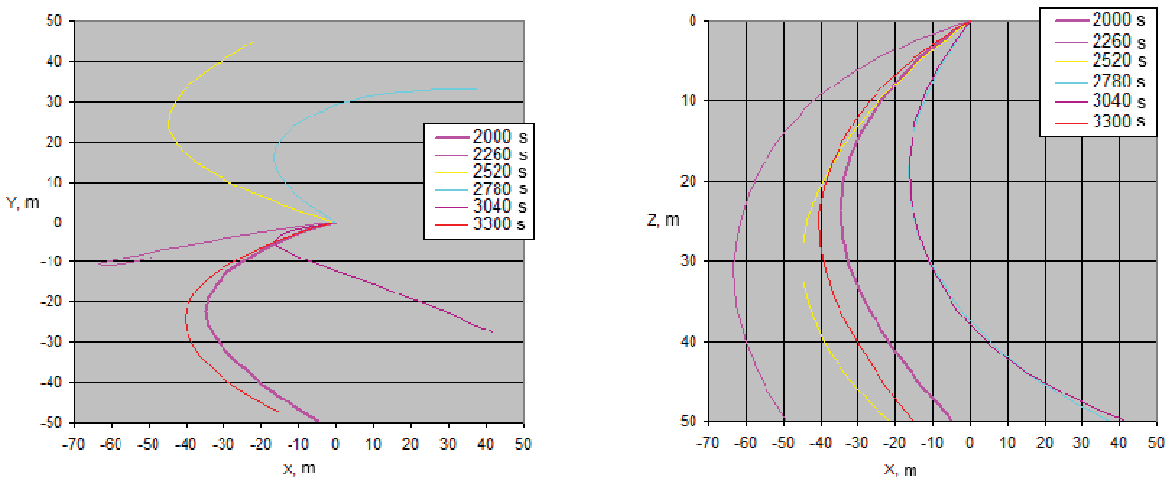

Fig. 13. Change in the shape of the FC connecting the CV and the UV during the UV movement projected onto the *X0Y* and *X0Z* planes (modeling results for Option 4)

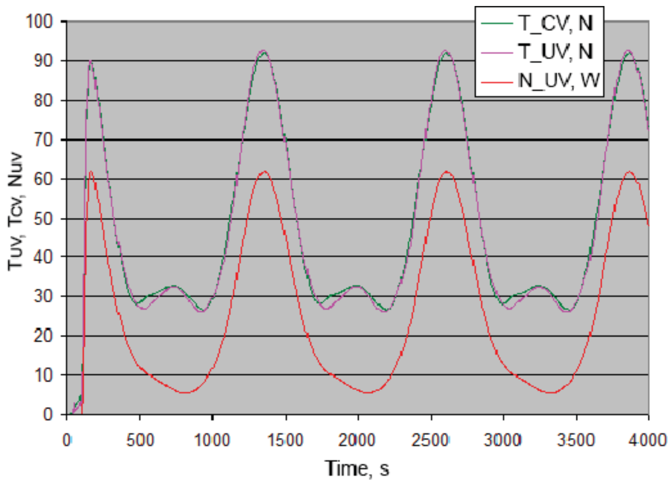

Fig. 14. Difference between the forces of the FC tension and the propulsor power

Option 5 also differs from Option 3 by the CV speed. Here, it moves along the *X* axis at the speed of 1 m/s. The modeling results are presented in Fig. 15 and 16.

An increase in the UV circulation speed significantly increases the demand power of the UV propulsor and the force of the FC tension.

Option 6. The CV moves along a circle with the radius of 100 m at the speed of 1 m/s, and a non-self-propelled UV moves behind it tethered by a FC 100 m long (Fig. 17). The center of the CV circulation is located at the point with the following coordinates: $X = 0$, $Y = -100$ m, $Z = 0$.

The FC position in space changes, but its shape hardly does (Fig.18).

The movement quickly reaches a steady state with slight oscillations of the forces of the FC tension acting on the CV and UV (Fig. 19). The UV moves behind the CV along a circle with a radius of ≈ 75 m at a depth of ≈ 55 m.

Option 7. The CV moves along a circle with the radius of 100 m at the speed of 1 m/s, and the non-self-propelled UV moves behind it tied to a FC 100 m long (Fig. 20). The UV is under a constant impact of the deflecting force of 100 N along the *Y* axis. The CV circulation center has the following coordinates: $X = 0$, $Y = -100$ m, $Z = 0$.

During the tethered system movement, the deflecting force distorts the shape of the FC and displaces the UV circulation center along the *Y* axis by approximately 25 m, i. e. the CV and UV circulation centers do not coincide. In the process of UV circulation, the depth of its immersion changes significantly (from 45 to 70 m).

At the steady state of the tethered system, the forces of the FC tension and the amplitude of their oscillations increase significantly (Fig. 21 and 22).

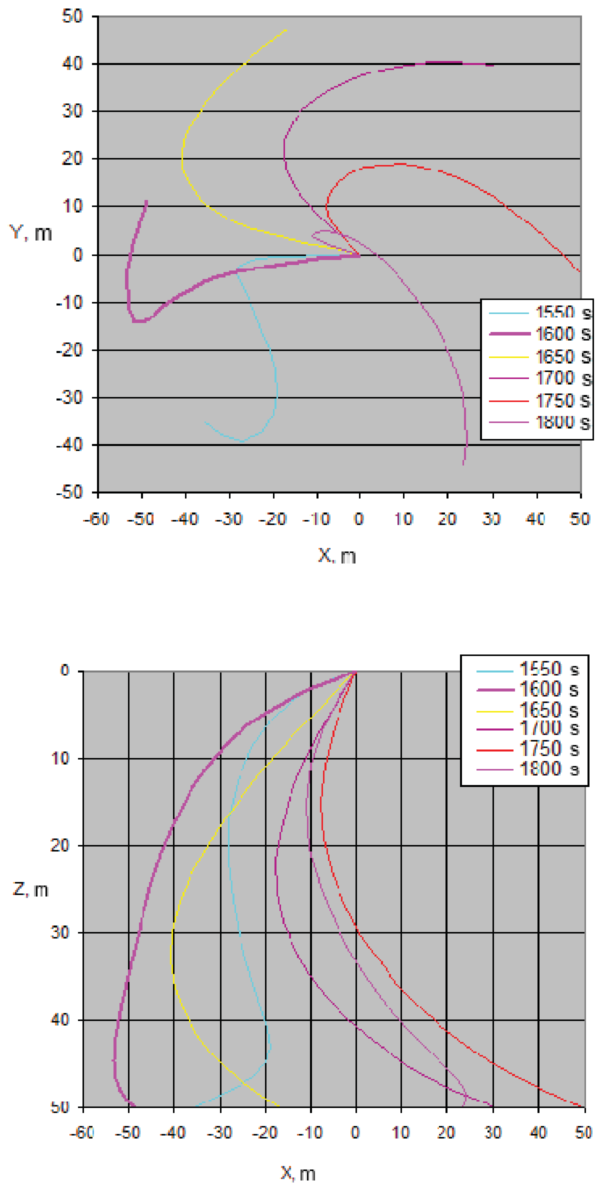

Fig. 15. Modeling results for Option 5

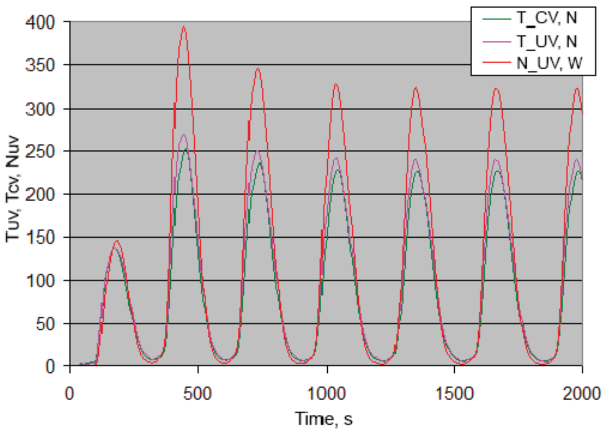

Fig. 16. Difference between the forces of the FC tension and the propulsor power

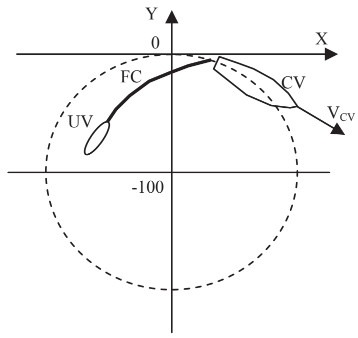

Fig. 17. CV moves along a circle with the radius of 100 m at the speed of 1 m/s, and a non-self-propelled UV moves behind it tethered by a FC 100 m long

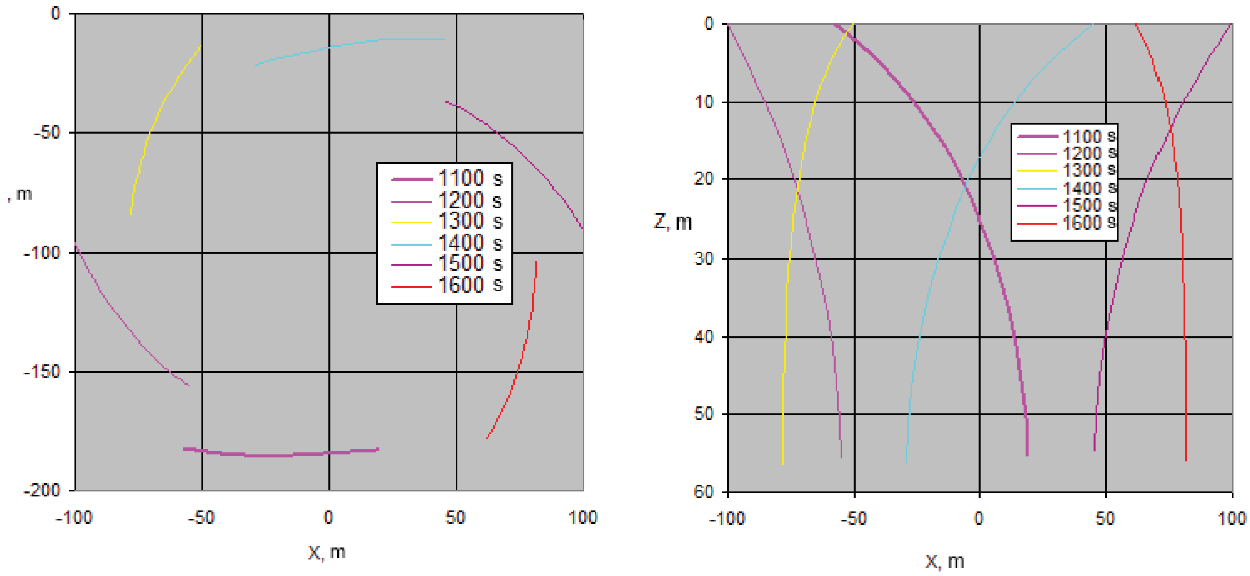

Fig. 18. The process of movement

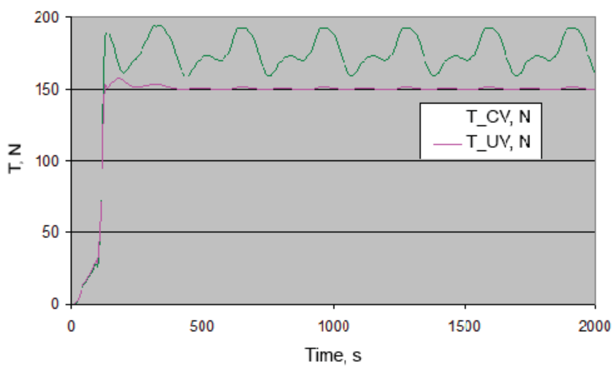

Fig. 19. Forces of tension acting on the CV and the UV

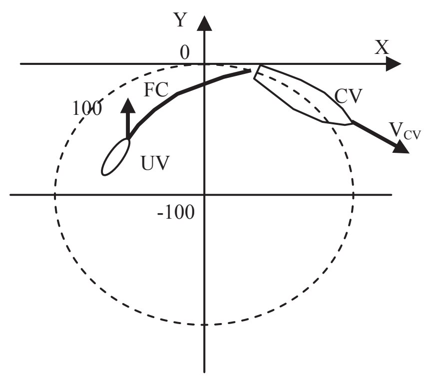

Fig. 20. CV moves along a circle with the radius of 100 m at the speed of 1 m/s, and the non-self-propelled UV moves behind it tied to a FC 100 m long

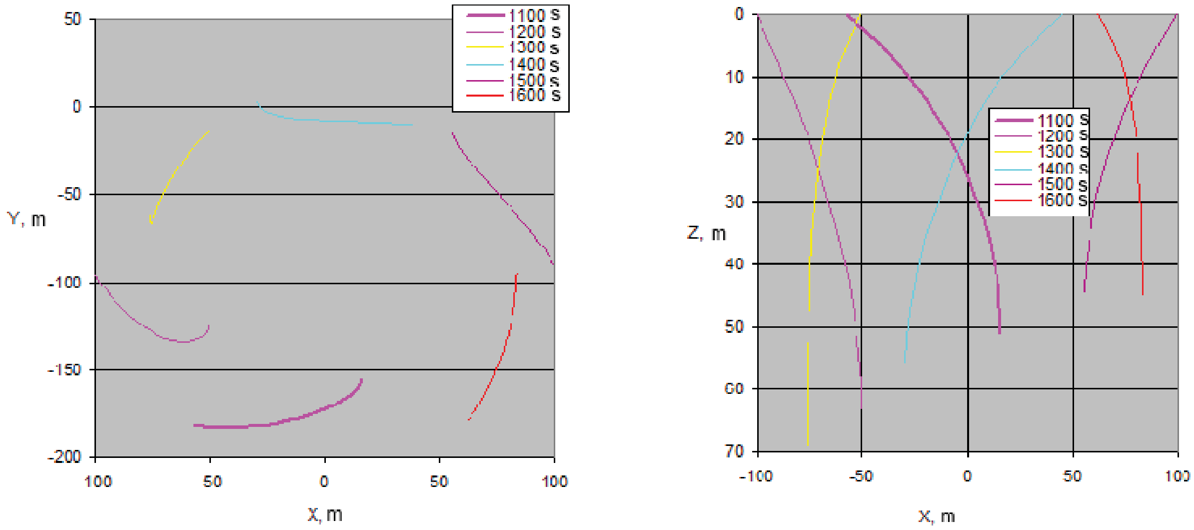

Fig. 21. The process of movement of a tethered system

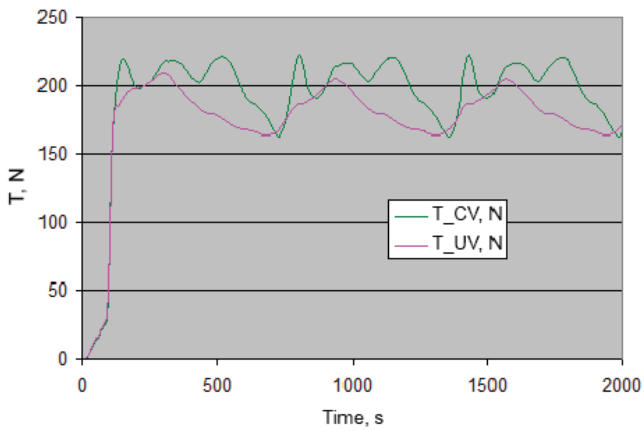

Fig. 22. Forces of tension acting on the CV and the UV

CONCLUSIONS.

The developed mathematical model and algorithm of the MTS FC dynamics (implemented as a computer model for describing the MTS FC dynamics) allow design engineers developing an MTS with FC to develop all the types of MTS in different operating and maneuvering modes with a higher quality and efficiency. The testing of the computer program of the MTS dynamics model for the circulation mode has demonstrated the program's operability and allows for its use in future practical calculations of the parameters of the MTS with FC.

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