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DETERMINATION OF ADDITIONAL TENSION IN TOWED STREAMER CABLE TRIGGERED BY COLLISION WITH UNDERWATER MOVING OBJECT

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ABSTRACT

The paper deals with issues connected with the behaviour of a streamer cable towed by a survey seismic vessel when the cable undergoes a strike triggered by collision with an underwater moving object. The consequences of such collisions may be both threat to the life of marine animals or damage to underwater units and large economic losses suffered by vessel owners. The risk of such collisions has increased over the last years as a result of increased offshore seismic survey operations. Therefore, a towed streamer should be very robust. To assure its robustness, we should know the deformation mechanism of a single streamer cable. This in turn requires the development of an appropriate mathematical model of such a phenomenon.
In particular, the paper presents the characteristics of seismic survey vessels and streamers; an analysis of collisions that have occurred in the past; a statement of the problem, and a computer-aided system supporting simulation of the cable behaviour. To obtain all the necessary design parameters regarding the deformation mechanism of a streamer cable, we set up a dedicated computer-aided system that supports their calculation.

Keywords: towed steamer cable, collision, deformation mechanism, offshore seismic survey

INTRODUCTION

In recent years, there has been intense growth in geophysical surveys related to the exploration of hydrocarbon resources located below the seabed. For this purpose, research vessels towing a complex array of related wires called streamers are used. Such an arrangement can occupy a very large area of sea reaching about 15 km^2. In accordance with the existing provisions, the entire search area is excluded from shipping. Therefore, other vessels must be informed about such an area by means of special warnings issued by Navtex and Inmarsat systems. These warnings are intended to avoid possible collisions between the research vessel and other floating units.

Nevertheless, there is still a possibility of collision with other objects occurring in the area of geophysical exploration, for example, with large-sized marine animals (cetaceans, dolphins) as well as underwater units (autonomous or remote-controlled underwater units). Consequences of such collisions may be:

- on the one hand, threats to the life of marine animals or damage to underwater units,
- on the other hand, damage to streamers, which could lead to the suspension of the survey for a certain period of time and consequently to very large economic losses by the research vessel ship-owner.

To minimize the effects of potential collisions, it would be useful to design a streamer system whose design would reduce the effects of possible collisions. This, in turn, requires knowledge of the deformation mechanism of a single streamer caused by impact during a collision.

The objective of this paper is to describe deformation mechanism of a single streamer triggered by a collision with underwater moving objects. There are several challenges to this approach that the paper will outline in the next sections. In particular, the paper presents the characteristics of seismic survey vessels and streamers; an analysis of collisions that have occurred in the past; a statement of the problem, and a computer-aided system supporting simulation of the cable behaviour. To obtain all necessary design parameters regarding the deformation mechanism of a single streamer, we set up a designed computer-aided system that supports their calculation.

The authors did not find any references in published journal papers that demonstrate the deformation mechanism of a single streamer triggered by a strike by underwater moving objects and techniques and would allow the calculation of the parameters of such a collision.

CHARACTERISTICS OF SEISMIC SURVEY VESSELS AND TOWED STREAMERS

Various offshore surveying techniques are used to locate geological structures that can trap oil or gas, namely seismic, magnetic, and gravity surveys [13]. Nevertheless, seismic survey techniques play a main role in locating of offshore oil and gas reserves [12]. All seismic surveys involve a source of hydro-acoustic energy and some configuration of receivers or sensors. There are three main types of seismic survey techniques:
- ocean bottom seismic techniques,
- vertical seismic profiles (VSPs),
- towed array of streamers.

Ocean bottom seismic techniques are based on acquisition with nodes and sensors located on the sea bottom. Vertical seismic profiling refers to measurements made in a vertical wellbore using geophones inside the wellbore and a source at the surface near the well.

Towed streamer operations represent the most significant commercial activity. The towing equipment enables the multiple streamers and source arrays to be positioned accurately behind the vessel. In these kinds of operations:
- The seismic survey vessel tows a "seismic streamer", or a collection of cables with seismic-source hydrophones attached,
- seismic acoustic sources use compressed air to produce hydroacoustic energy,
- receivers capture the returning sound waves.

The recordings received from seismic surveys are transformed into visual images of the subsurface of the sea bottom in the area of the seismic survey. Depending on the sea depth and the distance from the survey area to land, there are two types of towed streamer operations: shallow water and offshore seismic surveys.

A shallow-water/transition-zone seismic survey is a complex seismic operation as it is undertaken in shallow water [1]. The transition zone environment extends from onshore, where the presence of swamps and river estuaries makes conventional land or offshore acquisition techniques difficult or impossible, out to shallow marine environments, where deep-water offshore vessels cannot operate.

Seismic Survey Vessels (SSVs) are offshore units intended exclusively for the exploration of oil and gas resources under the sea bottom. SSVs have different sizes and shapes according to their functions. In shallow water acquisition, small conventional vessels are used. As a rule, their decks are additionally equipped with installations which enable geophysical surveys to be carried out. The specially designed SSVs are used in offshore acquisition. The most distinguishable offshore unit of the SSV type is Titan-class Ramform Thetys operated by the Norwegian ship-owner PSG [9]. This design, with its delta hull and spacious broad beam (Fig. 1), provides high stability in all sea conditions. A sinusoidal waterline allows stable motion behaviour at the beam. Meanwhile, the vast back deck is perfect for storing and towing an unprecedented array of acquisition equipment.

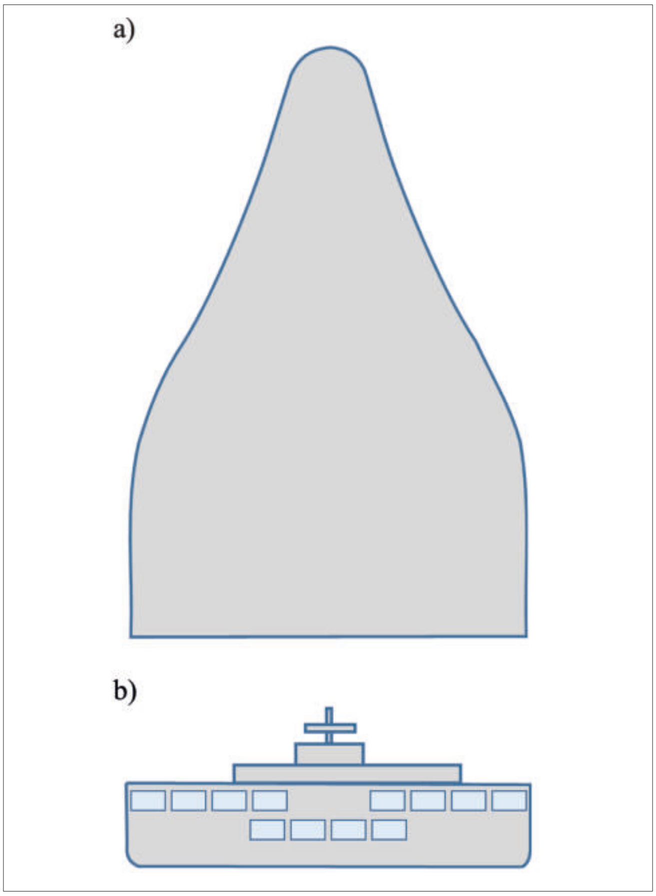


Fig. 1. Top view scheme of Seismic Survey Vessel –Ramform Thetys class Titan type: a) top view; a) back view

This ship, like the other ships of the Titan class, has a fairly specific shape: looking from the top, it is similar to a triangle (Fig. 1a). It is 104.2 m long and 70 m wide in the stern, which contains 24 streamer reels (Fig. 1b): 16 abreast and 8 in a second row.

This solution of the SSV makes it possible to deploy 24 streamers of 12 km in length with gaps of 100 m between them. Apparently, it is the largest moving object in the world created by mankind in terms of the surface covered. The towing force through the water can be compared with the towing capability of a bollard pull (300 tonnes) [9].

The key elements or areas of a typical offshore SSV are:
– an instrument room;
– a back deck, and;
– a compressor room.

The SSV instrument room is where the essential equipment necessary for a seismic survey is located, such as the computer aided system enabling data recording, the positioning system for the streamer array and sources of hydroacoustic energy, and the hydroacoustic wave activation system. The back deck of the SSV is designed for storage, deployment, and retrieval of the towed seismic equipment. Streamers are stored on large reels and, when acquisition is in progress, are deployed from the back of the vessel and towed directly behind the SSV (Fig. 1b). The compressor room of the SSV contains the compressor engines and compressors, which supply high-pressure air to the source arrays.

Seismic acoustic sources are attached to the immersed towed cables and generate an explosive wave by means of air guns. This operation consists in the sudden release of compressed air from a set of gun chambers of different volumes. On the signal given by the SSV instrument room, the compressed air is released and violent decompression produces a high-energy acoustic wave. Air guns are connected into columns and form a small matrix (Fig. 1a).

Receivers capturing the returning sound waves are key components of the acoustic wave recording system. They are embedded in the measuring streamer module, which is a complex circular section sandwich system in the form of a long cable segment (Fig. 2).

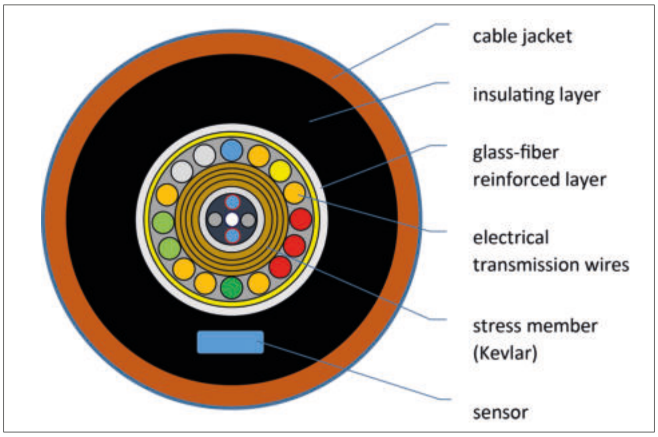


Fig. 2. Cross-section of the streamer cable structure

The streamer consists of four principal components: hydrophones, electronic modules, stress members, and electrical transmission systems.

The hydrophones convert the reflected pressure signals from a seismic source into electrical signals. Most hydrophones are based on a piezoelectric transducer that generates electricity when subjected to a pressure change. Hydrophones, grouped into several dozen units and assembled in a special housing, form a separate measuring module. Then, a set of hydrophones is embedded into the measuring modules in their insulation layer. The hydrophones are usually spaced about 1.0–3.0 m apart but are electrically coupled in groups 12.5 or 25.0 m in length. Each section is filled with electrical isolating fluid, which has a specific gravity of less than one, to make the overall streamer neutrally buoyant. The insulating layer located between the outer layer and the reinforced fibreglass layer is made of material with vibration damping properties. Although this fluid was historically an organic compound, more recently a purely synthetic material has been used.

The groups in the streamer are combined into sections, each 50–100 m in length, to allow modular replacement of damaged sections. Each section is terminated by a connector unit. The main task of electronic modules is to digitize and transmit the acquired signal along the streamer to the recording system on board the vessel where the data are stored. The stress members (steel or Kevlar) provide the physical strength required, allowing the streamer to be towed in the roughest of weather. The electrical transmission system makes it possible to transmit power to the streamer electronic modules and peripheral devices and to send telemetry data.

A set of parallel columns of streamers creates a matrix relevant to the recording of the acoustic waves reflected from ground layers located under the sea bottom. The rows of this matrix are the measuring streamer modules (Fig. 3).

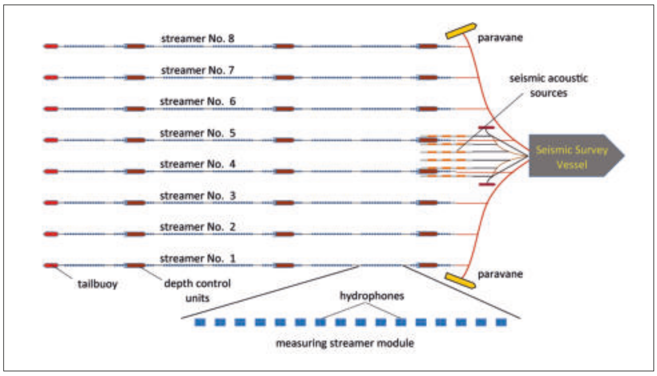


Fig. 3. Array of streamer cables towed by seismic survey vessel (top view)

The number of streamers depends on the SSV beam and can reach 24 columns. They are towed with controlled submersion under water (Fig. 4).

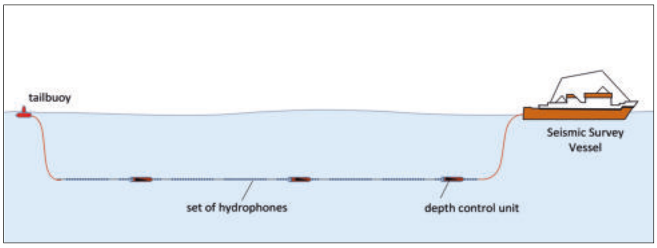


Fig. 4. Seismic streamer cable towed by seismic survey vessel with controlled submersion (side view)

This immersion varies depending on the size and is
– from 4 to 10 m in shallow waters;
– about 25 m on most offshore areas;
– up to 100 m in waters with a depth not exceeding 500 m.

The streamer length depends on the depth and type of the geological target for a given survey. Recent surveys in the North Sea have used streamer lengths of up to 8000 m, whereas in the Gulf of Mexico and offshore West Africa some surveys used streamers of up to 12000 m in length.

To obtain the appropriate seismic data, it is necessary to configure and maintain the desired geometry of the towed streamer and air gun arrays. To control the arrangement of streamers in a water plane and their immersion, special floating units assuring adequate buoyancy are used, namely paravanes (diverters, deflectors, deflector straps), tailbuoys, and depth control units or birds. Paravanes are towed through the water to maintain the streamer and air gun arrays in a certain position relative to the towing SSV. These arrays are connected by means of a special rigging system containing cross-connect cables and towed ropes. Tailbuoys are floating devices used to identify the end of a streamer and allow the seismic acquisition crew to monitor the location and direction of streamers. Depth control units or birds are used to control the depth of the streamer to an accuracy of typically +/– 1 m. In addition to the internal components, there are different types of external devices, which are sometimes attached to the streamer, such as flux gate compasses (often integrated within depth control units) and acoustic positioning units. These units are mounted externally onto a marine seismic streamer cable.

The results of position measurements received from the individual components are displayed on the control system screen in the SSV instrument room. They enable an operator (a seismic navigator) to continuously preview the spatial layout of the streamer and air guns matrixes and correct their configurations.

Depending on both the SSV's power and the sizes of the towed seismic survey equipment, the diameter of these cables varies from 14 to 70 cm [8], for example:

- the Geometrics DHA-7 eight-channel mini-streamer [6] has a diameter 14 cm and includes 8 hydrophone groups with 12 hydrophones per group, spaced 6.25 m apart with a total length of 150 m,
- the Teledyne Marine SDS-55 240-channel streamer [11] has a diameter of 55 cm and utilizes liquid crystal polymer stress members, a novel spacer approach, waterproof hydrophones, and ingenious connector designs.

OPERATIONAL PERFORMANCE AND COLLISION CONSEQUENCES OF OFFSHORE SEISMIC SURVEYS

The location, timing, and duration of an offshore seismic survey are dictated by the weather condition as well as the time of year when the survey is conducted. SSVs typically operate at a tow speed of between 4.5 and 5.0 knots. At this rate, they could conceivably cover some 200 km in a day and almost 6500 km in one month. As survey dimensions are not usually as great as 200 km, the SSV must turn at the end of each line before starting the next lap. With seismic streamers as long as 8000 m (with as many as 16 streamers being towed simultaneously behind the vessel), the time taken to change direction, or the line change time, may be up to 3 hours or more for the largest streamer configuration. For a survey with a line length of 45 km, which is fairly long even by today's standards, the line acquisition time of 5 hours is then followed by a line change of 3 hours or 60% of the acquisition time [1].

The offshore seismic survey is usually accompanied by one or more stoppageoffshore support vessels (OSVs). They are designed to ensure that other floating units do not interfere with the survey.

While a SSV is on survey, because of the slow towing speeds involved, the possibility of a ship strike with a marine mammal becomes negligible. Collisions between an SSV at speed and any of these species would possibly result in the mortality of the individual marine mammal [4]. At a speed of 4 knots, the risk of a vessel–whale collision resulting in lethal outcome is estimated as < 10% [7].

In terms of SSV-associated impacts, the International Association of Geophysical Contractors (IAGC) has noted that total vessel traffic in an area where a SSV is operating typically decreases as fishing and recreational vessels move out of the survey area to avoid vessel conflicts.

Collisions of seismic survey equipment with fixed objects are also rare. Unfortunately, when they happen, they can be quite expensive because the expenses of the offshore seismic survey are directly related to the costs of offshore operation. The main expense for these services is the vessel day rate. Day rates for a fully equipped and manned SSV are from 60000 to 200000 USD for 3D vessels and from 15000 to 45000 USD for 2D vessels [10].

Every time a seismic vessel with towed streamers is forced to abort a line due to an unforeseen event, roughly 6 hours are lost by turning around and starting over or moving to another line. At a rate of 150000 USD per day, each 6-hour break-off would cost the company 25000 USD. An example of such an expense is when a container ship ran over the tail end of an 8-km towed streamer array during a seismic survey in the Gulf of Mexico, causing a reported 25 million USD worth of damages [3].

Therefore, economic factors should be taken into consideration even in the case of negligible probability of collisions between the SSV and other objects occurring in the area of geophysical exploration. Moreover, the risk of collision will increase over the years as a result of an increased number of offshore seismic survey operations.

Therefore, a towed streamer should be highly robust, as mentioned above. To assure its robustness, we should know the deformation mechanism of a single streamer caused by a strike during a collision between the towed streamer and any obstacles moving underwater. This in turn requires the development of an appropriate mathematical model of such a phenomenon.

STATEMENT OF THE PROBLEM

Let us consider the case when a streamer is:

- towed with controlled submersion parallel to the seawater surface,
- subjected to an impact load caused by a collision with any underwater obstacle, such as an underwater towed unit, marine mammal, submarine, and so on.

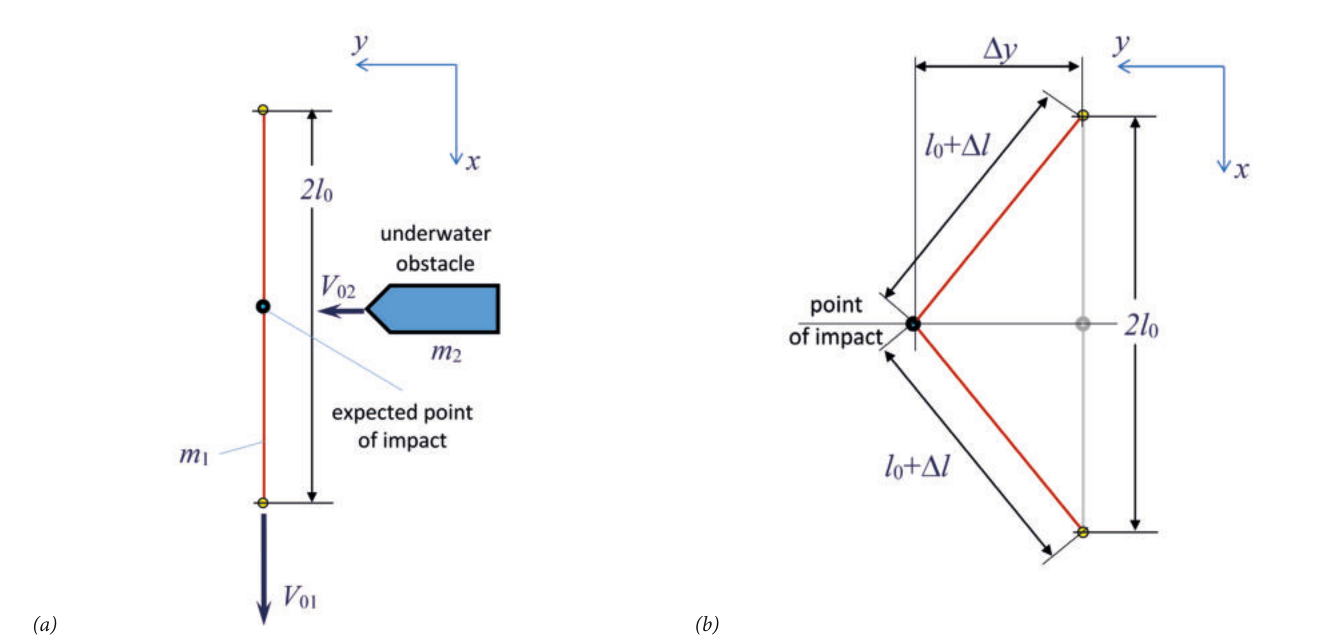


Fig. 5. Top view scheme of towed streamer with controlled submersion subjected to an impact load caused by a collision with any underwater obstacle: a) situation just before collision; a) situation after collision

Moreover, we assume that the velocity of the towed streamer V_{01} is constant. A stress member of the connected streamer cable segments (hereafter called a cable) provides the physical strength required, allowing the streamer to be towed in the roughest of weather. The cable is terminated by connector units on both sides. A top view of the situation just before collision is presented in Fig. 5a. The cable can be considered as a string with fixed ends with a body of mass m_1 which is stretched by the tension force T_0.

At a certain point in time, which is taken as the reference point $t = 0$, any underwater obstacles with a body of mass m^2 moving perpendicularly to the cable at velocity V_{02} come into contact with it. A scheme of the considered situation is presented in Fig. 5b.

Let us also assume that the collision occurs in the middle of the cable. Our task is to find the cable's additional tension force ΔT as a result of this collision. We can consider the cable as:

- an expandable weightless thread and
- an expandable thread with a point mass located at the point of impact.

To solve this task, we have taken into account the following preliminary assumptions:

- a lack of string motion associated with wave functions,
- a lack of the medium resistance during the string motion in water.

In the first case, the application of the conservation of energy principle provides a powerful tool for solving the presented problem. The principle of the conservation of mechanical energy states that the total mechanical energy in a system (i.e., the sum of the potential plus kinetic energies) remains constant as long as the only forces acting are conservative forces.

In the considered case, the kinetic energy K of the colliding objects is converted into the potential energy Π. This potential energy is stored in the cable as a result of its deformation, like the stretching of a spring [14].

For the Cartesian coordinate system connected rigidly with the towing vessel:

- the total kinetic energy K_{max} of the underwater obstacle and the weightless cable after the elastic collision equals:

$$K_{max} = \frac{m_0 \cdot V_0^2}{2} \tag{1}$$

where $V_0 = V_{01} + V_{02}$ and $m_0 = m_1 + m_2$.

- the total potential energy Π_{max} of one section of the two equal parts of the stretched cable (Fig. 5b) caused by the additional tension force ΔT equals:

$$\Pi_{max} = 2\int_0^{\Delta l_{max}} \Delta T \mathrm{d}(\Delta l) \tag{2}$$

where Δl is the elastic deformation (elongation) of each part of the cable as a result of the collision (Fig. 5b).

Within certain limits, the additional tension force ΔT caused by stretching of the expandable weightless cable is directly proportional to the extension of the spring. This is known as Hooke's law and can be written as follows:

$$\Delta T = c \cdot \frac{\Delta l}{l_0} \tag{3}$$

where:
ΔT is an additional tension force,
l_0 is the half length of the cable (Fig. 5a),
Δl is the elastic deformation of the cable,
c is a spring constant:

$$c = E \cdot F \tag{4}$$

where:
E is the Young's modulus of the cable,
F is the cross-sectional area of the cable stress member.

Finally, the additional tension force ΔT is:

$$\Delta T = E \cdot F\left(\frac{\Delta l}{l_0}\right) \tag{5}$$

It is worth noting that this additional tension ΔT depends on the geometric (F, l_0) and material (E) properties of the cable only.

The elastic deformation Δl (elongation) of the cable can be determined from the geometrical relations presented in Fig. 5b:

$$\Delta l = l(t) - l_0 = \sqrt{l_0^2 + y_0^2} - l_0 = \tag{6}$$

The total deformation will be as follows:

$$\Delta l_{max} \approx \frac{1}{2}\frac{y_{max}^2}{l_0} \tag{7}$$

where:
Δl_{max} is the maximal deformation of the cable triggered by the collision.

Now, the total potential energy Π_{max} caused by the additional tension force ΔT equals:

$$\Pi_{max} = 2\int_0^{\Delta l_{max}} c \cdot \Delta l \mathrm{d}(\Delta l) = c \cdot \Delta l^2_{max} \tag{8}$$

Now, taking into account that both the kinetic energy (1) and the potential energy (8) of the colliding objects are equal:

$$K_{max} = \Pi_{max} \tag{9}$$

we get:

$$\frac{m_0 \cdot V_0^2}{2} = c \cdot \Delta l^2_{max} \tag{10}$$

Then, the maximal deformation Δl_{max} of the cable is:

$$\Delta l_{max} = \sqrt{\frac{m_0 \cdot V_0^2}{2c}} = V_0\sqrt{\frac{m_0}{2c}} \tag{11}$$

whereas the maximal dynamic additional tension force (3) is equal to:

$$\Delta T_{max} = c \cdot \Delta l_{max} = V_0\sqrt{\frac{c \cdot m_0}{2}} \tag{12}$$

Now substituting the dependency for the spring constant c (4) in the obtained equation (12), we get:

$$\Delta T_{max} = V_0\sqrt{\frac{E \cdot F \cdot m_0}{2l_0}} \tag{13}$$

After a series of transformations, we can obtain a slightly different representation for ΔT:

$$\Delta T = \rho_0 \cdot V_0 \cdot a_0\sqrt{\frac{m_2}{m_1}} \tag{14}$$

where:
ρ_0 is the density of the cable stress member material.

In the second case, taking into account the inertial properties of the cable, we could consider the towing steamer segment as an extensible thread with an equivalent point mass m_1 located at the point of impact.

To determine the equivalent mass of the cable m_1 in the form of a concentrated load, we can use the equations of string and load motions respectively. The string motion equation (known as a simple harmonic oscillator) is as follows:

$$\frac{\mathrm{d}^2y}{\mathrm{d}t^2} + \omega_0^2 \cdot y = 0 \tag{15}$$

where ω_0 is the angular frequency of string oscillations:

$$\omega_0 = \frac{\pi}{2l_0}\sqrt{\frac{T_0}{q}} \tag{16}$$

and q is the cable linear density (that is, the mass per unit length).

The load motion equation is expressed as:

$$\frac{\mathrm{d}^2y}{\mathrm{d}t^2} + k^2 \cdot y = 0 \tag{17}$$

where k is the natural frequency of free vibration for a system without damping:

$$k = \sqrt{\frac{2T_0}{l_0 \cdot m_1}} \tag{18}$$

Comparing the coefficients ω_0 (16) and k (18) of both equations describing string motion, we can determine the equivalent mass of the load:

$$m_1 = \frac{4l_0}{\pi^2} \cdot y \approx 0{,}8\ (\rho_0 \cdot l_0 \cdot F) \tag{19}$$

When an object of mass m_2 moving at a speed of V_{02} strikes a cable with equivalent mass m_1 moving at a speed of V_{01}, the whole system will have a speed of:

$$V_0 = (V_{01} + V_{02})\frac{m_2}{m_1 + m_2} \tag{20}$$

Therefore, the kinetic energy K of the whole system can be written as:

$$K = (m_1 + m_2)\frac{V_0^2}{2} \tag{21}$$

The potential energy Π of the tensioned cable can be determined by (2) or can be expressed as follows:

$$\Pi_m = c \cdot l_0\left(\frac{\Delta l}{l_0}\right)^2 \tag{22}$$

Comparing the energies expressed by (21) and (22) respectively, we obtain:

$$(m_1 + m_2)\frac{V_0^2}{2} = c \cdot l_0\left(\frac{\Delta l}{l_0}\right)^2 \tag{23}$$

Taking into consideration (4) and (20) and determining from (23) the cable's fractional elongation, we get:

$$\frac{\Delta l}{l_0} = \frac{(V_{01} + V_{02})}{\sqrt{2E \cdot F \cdot l_0}} \sqrt{\frac{m_1}{1 + \frac{m_1}{m_2}}} \tag{24}$$

Substituting the above received relation (24) into (3) expresses the additional tension force ΔT, we obtain:

$$\Delta T = (V_{01} + V_{02}) \sqrt{\frac{E \cdot F \cdot l m_2}{2l_0 + (1 + \frac{m_1}{m_2})}} \tag{25}$$

The value of the total cable tension is defined as the sum of the static and dynamic components is equal to:

$$T = T_0 + \Delta T \tag{26}$$

In this way, we obtain two equations that will allow us to calculate the total tension in the towed streamer segment as a result of its collision with the underwater obstacle when the cable is considered as:

– an expandable weightless thread (14),
– an expandable thread with a point mass located at the point of impact (25).

Based on the analysis of these equations, we can state that consideration of the cable mass leads to a decrease in the dynamic tension in the cable.

It was mentioned earlier that both equations (14) and (25) are approximations, since they take into account neither the wave processes in the cable nor the water resistance during the cable motion.

Now, our task is to justify the possibility of using Eq. (25) to determine the maximum tension force in the towed streamer segment as a result of its collision with the underwater obstacle. This equation assumed straightness of the streamer segment between the impact point of any underwater obstacle and the streamer connector units considered as string fixed ends, as well as the absence of losses due to the hydrodynamic friction of the towed streamer.

COMPUTER-AIDED SYSTEM SUPPORTING SIMULATION OF THE CABLE BEHAVIOUR AND DISCUSSION

To solve the problem formulated in the preceding paragraph, we apply:

– the developed mathematical model of two connected flexible components of the marine towed cable presented in [2, 16],
– the computer-aided system presented in [15] to enable simulation and calculation of the dynamic tension in the cable obtained based on this developed mathematical model.

The developed mathematical model described the dynamics of the marine towed system by means of a set of partial differential equations. This system includes the following components: a vessel, a streamer segment, and a whole towed cable. The applied set of equations depends on the parameters characterizing the properties of this system and the external impacts on it.

Based on the developed mathematical model, we are able to observe the dynamics of the marine towed cable as a result of external forces and reactions of its elongation, bending, and turning. More information can be found in [2].

To demonstrate the working principle of the computer-aided system for observation of the simulation process, let us assume that the towed streamer segment has a length of 1000 m, a diameter of 14 mm, and a Young's modulus of $9.55 \cdot 10^8$ Pa, the cable linear density is 0.15386 kg/m, and the normal and tangential coefficients of streamer hydrodynamic drag are zero. Moreover both the SSV and the towed streamer (TS) are motionless. At the initial moment of time, the streamer segment (SS) is at rest, located horizontally, and has the shape of a straight line. The value of its tension is zero. Then, at the midpoint of its length, there is a collision with an object of mass m_2, which moves perpendicular to the SS with the initial speed . A section of the computer-aided system with input parameters is shown in Fig. 6, while a section for observation of the simulation progress is presented in Fig. 7.

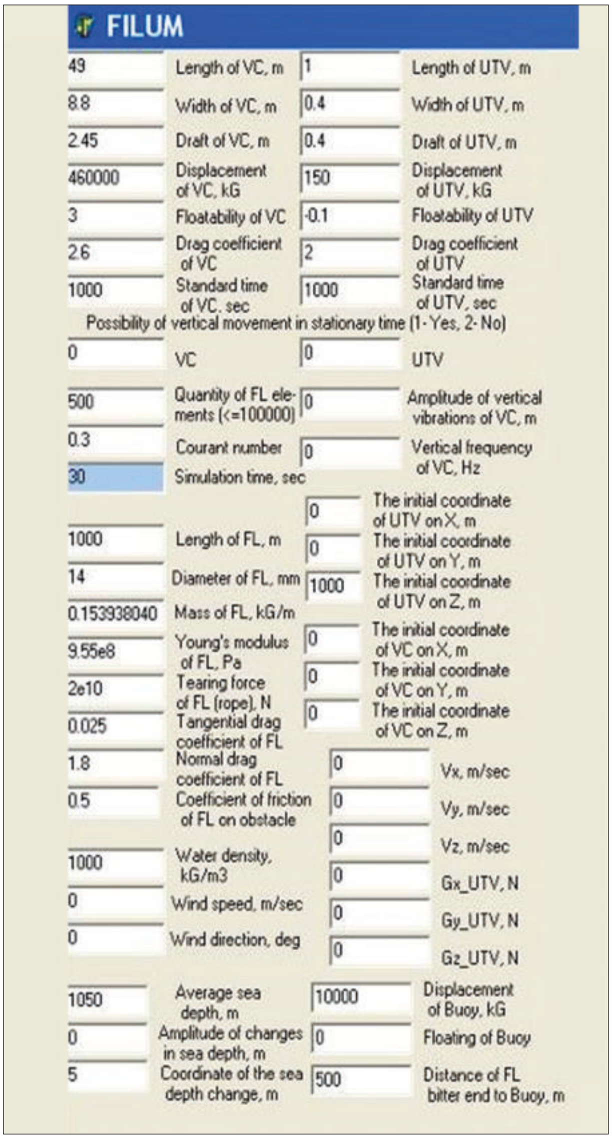


Fig. 6. Screen (fragment) of the computer-aided system with input parameters introduced

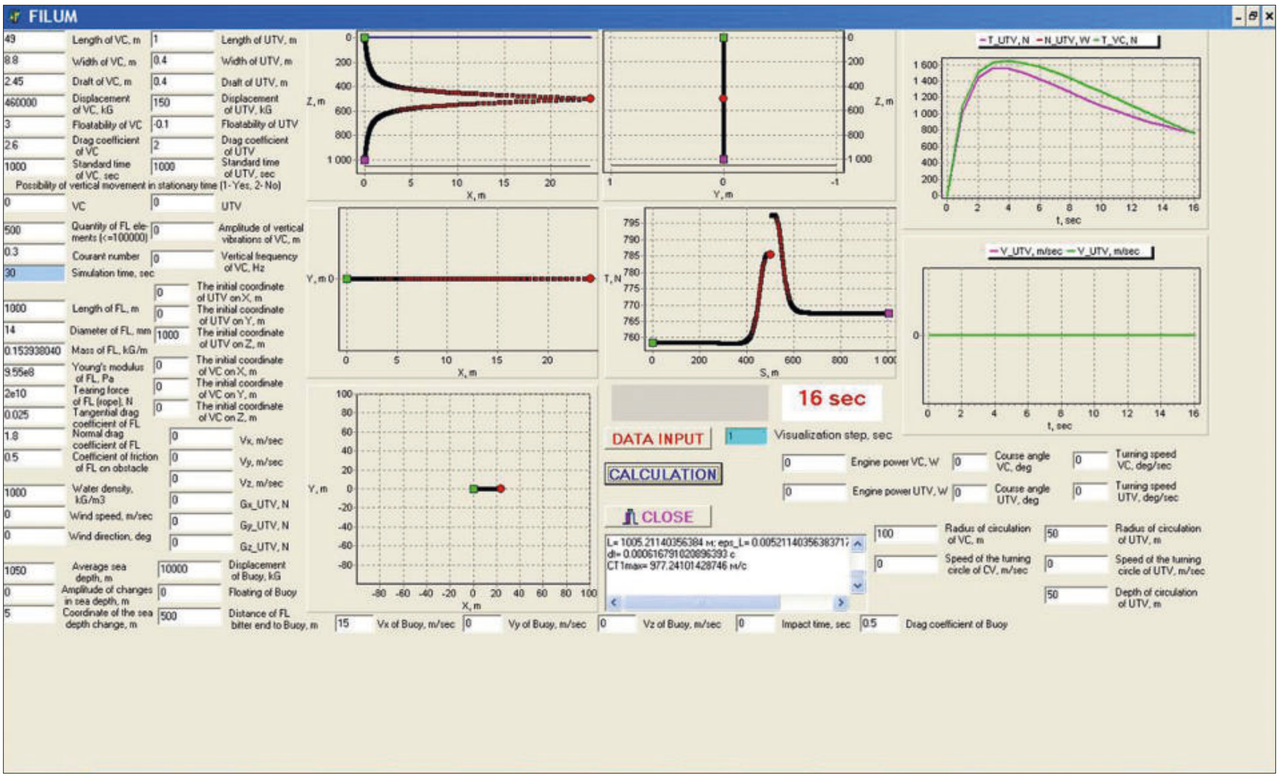


Fig. 7. Screen (fragment) of the computer-aided system for observation of the simulation process

The results of the simulation show that the shape of the SS during its interaction with the underwater obstacle (UO) differs significantly from a linear shape (Table 1). In the simulation, we assumed that the UO remains in permanent contact with the SS (it is not released from it) throughout the entire duration of its movement, in both the positive and the negative direction. The simulation time was chosen arbitrarily and amounted to 30 sec.

The diagrams presented in Table 1 show the shapes of the SS that are the most characteristic of this case for the arbitrary chosen times. (*Table 1, next page*)

The SS tension force during the time of observation changed significantly (Fig. 8) and both the SS and UO performed damped oscillations, indicating a significant influence of fluid resistance forces.

The shape of the SS at its maximum tension force corresponds to the assumptions that were used in the development of Eq. (25) (for m = 100 tons and V_0 = 15 m/s respectively).

Taking into account the hydrodynamic resistance perpendicular to the horizontal axis, we can notice that the shape of the cable during its maximum tension differs significantly from the shape obtained from Eq. (25). It depends on the UO mass, which is confirmed by the diagrams presented in Fig. 9.

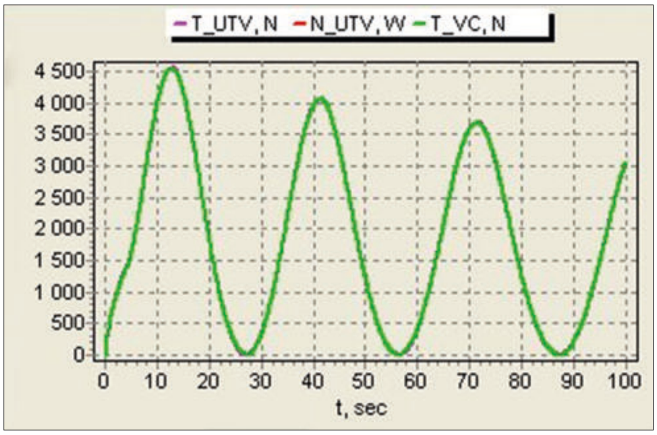
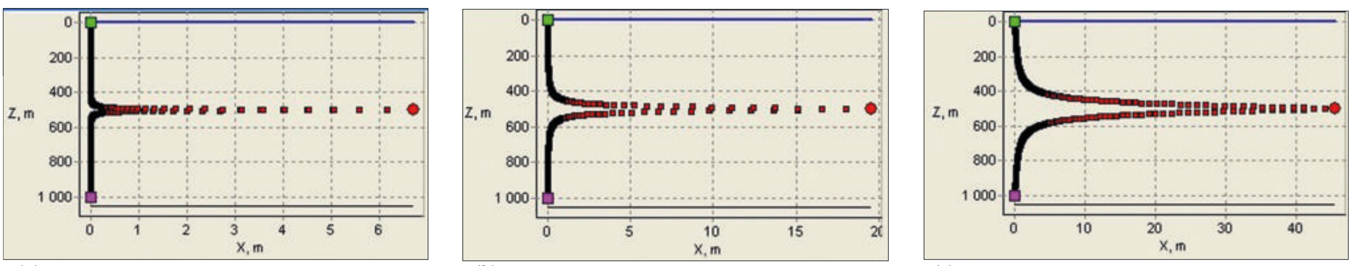


Fig. 8. Diagram showing the change of the SS tension force



(a) (b) (c)

Fig. 9. The shape of the SS at its maximum deflection: a) for mass = 1 tons; b) for mass = 10 tons; c) for mass = 100 tons

Table 1. The simulation results of collision between SS and UO

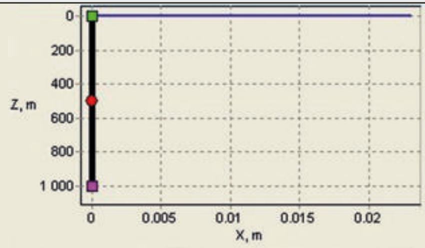
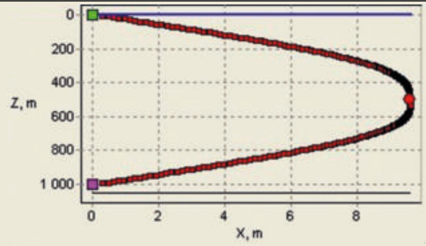
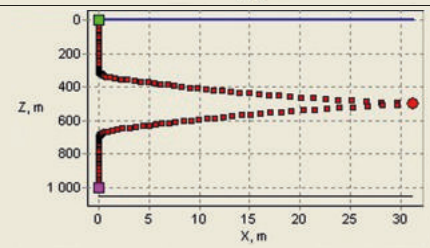
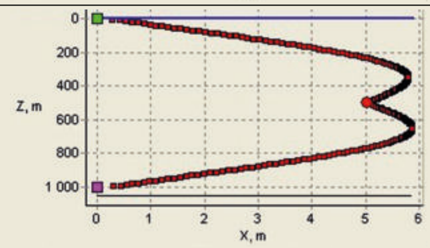
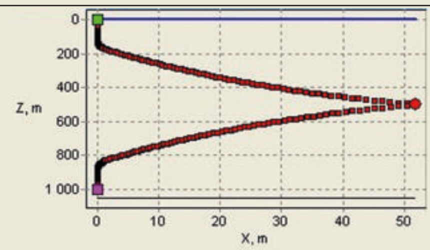
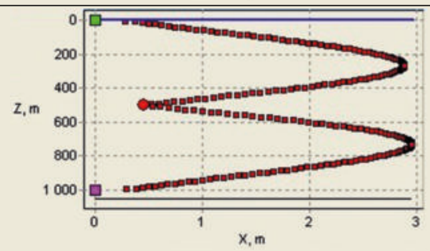
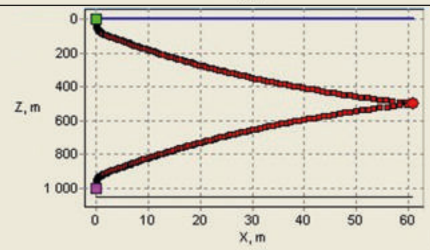
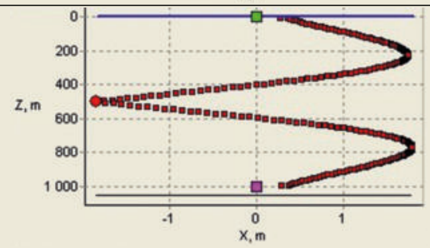
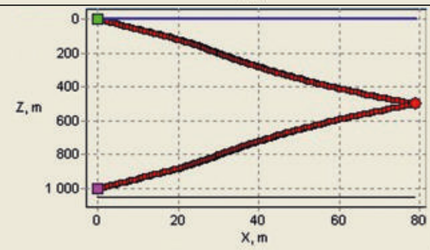
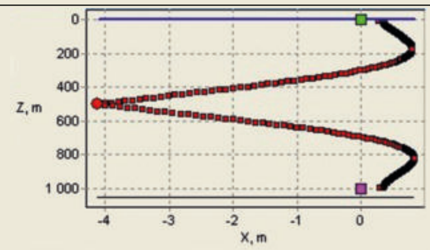
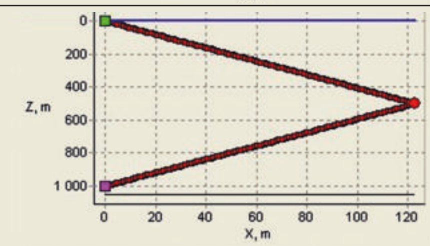
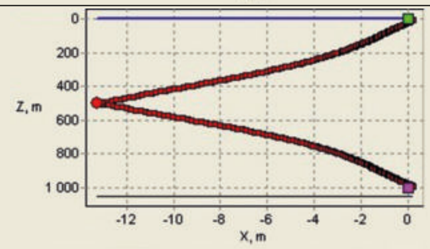
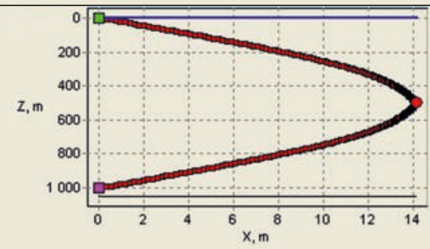
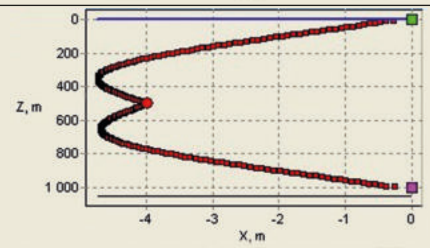
	From of SS		From of SS
1	2	1	2
0.0		26.3	
2.1		26.7	
3.6		27.1	
4.3		27.3	
5.8		27.5	
14.4		28.4	
25.9		56.0	

Table 2. The results of calculations of the SS tension force

	m [tons]			
	1.0		10.0	
V_0 [m/sec]	ΔT_{eq} [kN]	ΔT_{CAS} [kN]	ΔT_{eq} [kN]	ΔT_{CAS} [kN]
0.0	0.00	0	0	0
1.0	0.38	0.37	1.2	1.05
3.0	1.15	1.085	3.6	3.016
5.0	1.92	1.765	6.1	4.76
10.0	3.83	3.31	12.1	8.58
15.0	5.75	4.55	18.2	11.86
20.0	7.67	5.48	24.3	14.71
25.0	9.58	6.16	30.3	17.23
30.0	11.50	6.65	36.4	19.48

For the previously adopted parameters (towed streamer segment = 1000 m, towed streamer diameter = 14 mm, Young's modulus = 9.55×10^8 Pa), the results of calculations of the SS tension force ΔT obtained using both Eq. (25) and the dedicated computer-aided system respectively are presented in Table 2.

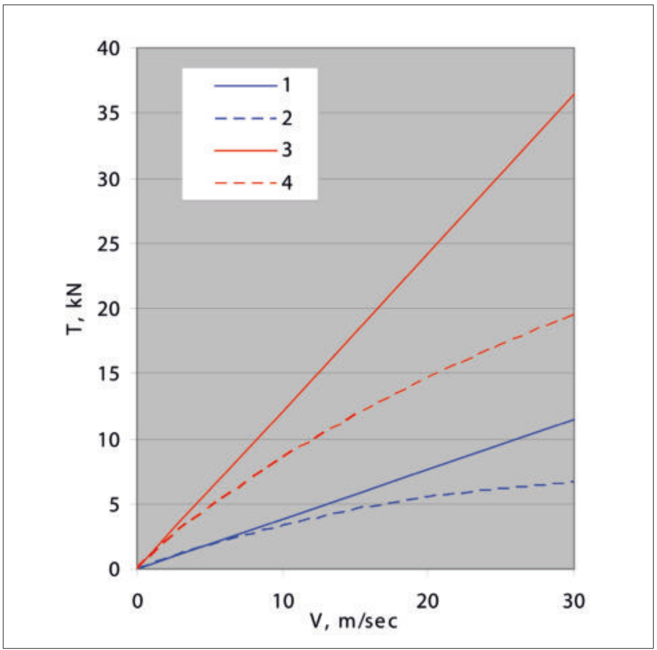


Fig. 10. Dependences of the SS maximum tension forces at the velocity V_0 obtained by means of Eq. (25) (denoted by 1 and 3) and the computer-aided system

The results of comparing the dependences of the SS maximum tension force ΔT at the velocity V_0 obtained by means of Eq. (25) and the computer-aided system are presented in Fig. 10.

Based on these comparisons, we can state that the results obtained by means of Eq. (25) are applicable if the UO mass m is less than 10 tons and its initial speed V_0, is less than 4 m/sec. Otherwise, use of Eq. (25) for calculation of the SS maximum tension force ΔT gives us significantly overestimated results.

CONCLUSIONS

The developed mathematical models and computer-aided system supporting simulation of the towed steamer cable behaviour as well as the performed analysis of the simulation results permitted us to formulate the following conclusions:

- using both the developed mathematical model and the computer-aided system for description of the towed streamer dynamics after collision with the moving underwater obstacle allows clarification of the classical mathematical model used to calculate its maximum tension force,
- the existing mathematical models have some limitations and can only be used for relatively small underwater obstacle masses and velocities,
- the developed tools allow us to understand the deformation mechanism more deeply, which, in turn, could allow the design of towed streamer cables with the required robustness to withstand impact by any underwater floating obstacle.

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