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MATHEMATICAL AND PHYSICAL BASIS FOR DEVELOPING A SIMULATOR FOR TOWING AND PULLING OF WHEELED AND TRACKED MACHINES

Abstract. The subject matter of the article is the towing and pulling of wheeled and tracked vehicles with the use of cable ropes and dynamic slings. The **goal** of the study is to determine the mathematical and physical basis for the development of a simulator for towing and pulling wheeled and tracked vehicles for researching to study the possibility of using aramid fibers of cable-ropes and dynamic slings. **The tasks** to be solved are: based on the analysis of the main roads and ground characteristics to formalize the list of calculated parameters and physical quantities determine the amount of evacuation work when pulling, towing and transporting wheeled and tracked vehicles; to develop a mathematical model that describes the process of pulling and towing wheeled and tracked vehicles using cable ropes and dynamic slings. General scientific and special **methods** of scientific knowledge are used. The following **results** are obtained. By analyzing the main characteristics of roads and ground, a formalized list of design parameters and physical quantities that determine the volume of evacuation work during the towing and pulling of wheeled and tracked vehicles was obtained. Mathematical model, describes the process of pulling and towing wheeled and tracked machines using cable ropes and dynamic slings have been compiled as a system of equations with different order. analyzed existing technology for the production of aramid fibers, their strengths and weaknesses, and formed a research polygon with regard to the peculiarities of the operation of wheeled and tracked vehicles. Existing technology for the production of aramid fibers, their strengths and weaknesses, and formed a research polygon with regard to the peculiarities of the operation of wheeled and tracked vehicles have been analyzed. **Conclusions.** The main roads and ground characteristics that determine the vehicles. evacuation conditions are the following: the type of road or ground, their possibility depending on the season and precipitation, the presence of ascents and descents, as well as the nature of road (ground) interaction with caterpillars determined by resistance coefficients. movement and traction. The mathematical model of pulling a wheeled and tracked vehicle using cable ropes and dynamic can be presented as a system of equations: the jerk carried out by the machine in time reflected third-order differential equation, assuming that all the energy accumulated by the cable is numerically equal to the work of moving stuck machine, corresponds to the equality of the corresponding integrals; the properties of aramid fibers that affect the strength and performance characteristics of cable ropes can be formally expressed through the elongation of the cable. Analysis of strength and service properties of aramid fibers opens the way to improvement of manufacturing technology of cable ropes and dynamic slings for pulling and towing of wheeled and tracked vehicles.

Keywords: towing and pulling of wheeled and tracked vehicles; cable ropes and dynamic slings; strength and performance characteristics of aramid fibers; the mathematical model of pulling a wheeled and tracked vehicle.

Introduction

Formulation of the problem and research tasks. It is well known that the immediate evacuation of wheeled and tracked vehicles (WTV), in particular armored weapons and military equipment (AMWE), facilitates the rapid return of the equipment to action and, in the time of combat, also prevents it from being destroyed or captured by the enemy. Vehicle recovery is a complex technical task which is often hindered by the use of towing cables with their lack of strength and serviceability. Traditionally, steel cables left over from the Soviet Army are used to evacuate vehicles. The appropriate method of AMWE evacuation relevanted at that time and designed for low-skilled personnel, is not only time- and resource-intensive and non-ergonomic, but also very dangerous. At the same time, the emergence of new technologies in the production of tow ropes and dynamic slings has expanded the possibilities of use for the manufacture of the last fibers with more attractive performance and strength properties.

Modern aramid fibers have the highest tensile strength and modulus of elasticity, if we consider the ratio of these indicators to their density. They are resistant to most conventional organic solvents, combustibles and lubricants. Under the action of very strong acids and alkalis, its strength decreases, but it is more resistant to corrosion factors, such as salt water. Therefore, the possibility of using cable-ropes made of modern aramid fibers for pulling and towing AMWE require additional research. It is clear that the cost of field experiments due to their destructive nature is too high. Physical modeling is also not a suitable method of analyzing the effectiveness of hostilities due to the difficulty of finding an adequate physical analogue to the processes that take place during hostilities.

Thus, the actual is problem to develop new methods of evaluation of the use of existing technologies both to assess the feasibility and to identify methods of using aramid fibers cable-ropes and dynamic slings for the towing and pulling the coils.

Analysis of recent research and publications on the above issues shows the relevance of the study. The order of organization of evacuation of tanks, methodology of calculation of tractive forces for different types of jams; order of loading of tanks on vehicles are presented almost without changes in textbooks that have been published during the last ten years [1, 2]. The material submitted in the style of advice and instructions, of course, is easy to digest, but does not reveal the mathematical and physical principles of towing and hauling of wheeled and tracked machines and, The design is not intended to be used as a basis for investigating the feasibility of using aramid fiber cable ties and dynamical slings.

The methodology for calculating the forces acting on the towing objects from the side of the towing link used in the modeling of the towing process, has been considered quite thoroughly for marine objects [3], but its use for WTV samples requires some refinement due to the specific conditions of the application.

The goal of the study is to determine the mathematical and physical basis for the development of a simulator for towing and pulling wheeled and tracked vehicles for researching to study the possibility of using aramid fibers of cable-ropes and dynamic slings. To achieve this goal the following **research tasks** are solved:

– based on the analysis of the main roads and ground characteristics to formalize the list of calculated parameters and physical quantities determine the amount of evacuation work when pulling, towing and transporting wheeled and tracked vehicles;

– to develop a mathematical model that describes the process of pulling and towing wheeled and tracked vehicles using cable ropes and dynamic slings;

– to analyze the existing technologies for the production of aramid fibers, their advantages and disadvantages, and to draw conclusions about the feasibility of additional processing of aramid fibers, given the peculiarities of the operation of wheeled and tracked vehicles.

Main material

1. Roads and ground characteristics and a list of calculated parameters and physical quantities that determine the evacuation work amount during the towing and pulling WTV samples. The nature and scope of evacuation work during the towing and pulling of WTV samples largely depend on the condition of roads and ground. The main roads and ground characteristics that determine the vehicles. evacuation conditions are the following: the type of road or ground, their possibility depending on the season and precipitation, the presence of ascents and descents, as well as the nature of road (ground) interaction with caterpillars determined by resistance coefficients. movement and traction.

To compile the differential equations of the process of pulling and towing wheeled and tracked machines, we will use the following provisions. The possibility of machines on all ground is determined by the coefficients of adhesion and drag.

The resistance to movement resulting from the interaction of the tracked vehicle with the ground and ground deformation is characterized by the drag coefficient *f*. The resistance of the WTV caterpillar depends on the design parameters of the caterpillar, the cost of friction in the chassis and some transmission units, ground quality and speed.

The greatest force with which the ground keeps the tracks from slipping is called the traction force by traction, which is characterized by the track-to-gravel coefficient φ. The traction coefficient depends on the quality of the ground, the specific pressure of the crawler and the design of the tracks. The drag and traction coefficients for the tracked vehicles for the most typical road conditions obtained by experiment [1, 2, 4].

2. Mathematical model for the evacuation of wheeled and tracked vehicles using cable ropes and dynamic slings.

2.1. To successfully carry out evacuation work, it is necessary to correctly determine the traction forces required for the towing and pulling of the WTV and the evacuation capabilities of the available traction means. Let a vehicle of mass *M* get stuck, having gone deep into the ground with certain characteristics to a depth *h*, having an angle of inclination α and an divergence angle of the tractive effort with the direction of movement *β* (Fig. 1).

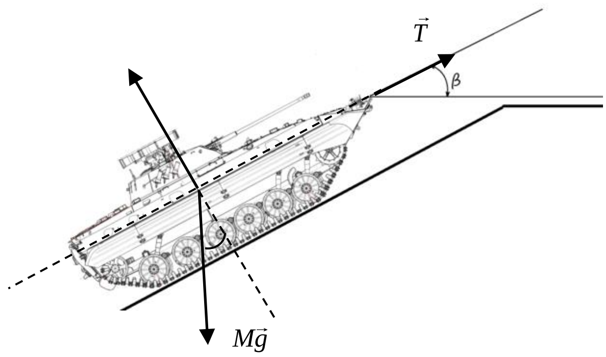

Fig. 1. Forces acting on the WTV sample during towing and pulling

When towing and pulling the machine, it is necessary to overcome the resistance force R, which depends on many reasons - technical condition of the machine, ground conditions, depth of the jam, angle of inclination, etc. According to [1], the value of *R* is calculated as the sum of the main resistance (the so-called ground drag) R_1 and the additional resistance R_2

$$R = R_1 + R_2 , \quad (1)$$

where R_1 takes into account the takes into account sliding friction on the ground *f*, the ground tilt angle α and the depth *h*.

R_2 takes into account the difference between the tractive force strength and the angle deviation machine's displacement strength β, the additional length at continuous stalling or at hardening or shrinking of the ground; the coefficient of aggregation with the ground in case of jamming of the running gear of the machine.

For example (Fig. 1), will consider for the car with a serviceable running gear:

$$R_1 = Mg(f \cos\alpha + \sin\alpha) . \quad (2)$$

When jamming the running gear R_1 is determined by the formula:

$$R_1 = Mg(\phi \cos\alpha + \sin\alpha) , \quad (3)$$

here *M* – mass of the vehicle; *f* and φ – the coefficients of resistance to motion and adhesion, respectively.

2.2. Assume that the machine is pulled and towed by a tractor, the traction capabilities of which allow you to create traction on the hook of the tractor in these road conditions. This force is transmitted by a cable whose pulling force T acts on the machine. When pulling and towing, the machine will move with acceleration $\vec{a}$.

Based on this, according to Newton's second law, we can write:

$$\vec{T}+M\vec{g}+\vec{R}=M\vec{a} \qquad (4)$$

Expression (4) neglects the mass of the cable itself. Taking into account the mass of the cable m, it will look like

$$\vec{T}+(M+m)\vec{g}+\vec{R}=M\vec{a}\ ,$$

Here T – cable pulling force; R – resistance force; a – machine acceleration; M – vehicle's mass; m – cable's mass; g – acceleration of gravity.

If we assume that the cable has length l and is made of a material with density ρ, then the expression () will have the form

$$\vec{T}+(M+\rho l)\vec{g}+\vec{R}=M\vec{a}\ . \qquad (5)$$

Pulling and towing can be done jerkily. This means the volatility of the acceleration can over time. From time to time the machine will pass the distance S, changing its position $x(t)$. Given that

$$a(t)=\frac{dv(t)}{dt}=\frac{d^2x(t)}{dt^2}\ , \qquad (6)$$

the (5) can be designed and written in scalar form:

$$T-((M+\rho lS)g\sin\beta+R\cos\beta)=M\frac{d^2x}{dt^2}\ , \qquad (7)$$

here f – sliding friction on the ground; α – the ground tilt angle; β – angle deviation machine's displacement strength; T – cable pulling force; R – resistance force; l – cable's length; ρ – cable's density. S – rope diameter.

In these calculations it is assumed that the rope consists of one strand. If a cable is stranded with n, then the tension is multiplied by n.

At the same time, the force T is also not constant, because the cable has damping properties. We will assume that all the energy accumulated by the cable-cable is numerically equal to the work of moving the stuck vehicle. In analytical form, this equality will look like

$$\int_{l}^{l+\Delta l} Tdl=\int_{x_{in}}^{x_f}(M\frac{d^2x}{dt^2})dx\ , \qquad (8)$$

here x_{in} – initial position of the vehicle; x_f – final position of the vehicle; M – mass of the vehicle; T – cable pulling force.

After transforming the formula, we get

$$\int_{l}^{l+\Delta l} Tdl=\int_{x_{поч}}^{x_{кін}}(M\frac{d^2x}{dt^2})dx=\int_{t_{поч}}^{t_{кін}} M\frac{d^2x}{dt^2}v(t)dt=$$

$$=\int_{t_{in}}^{t_f} M\frac{d^2x}{dt^2}\int_{t_{in}}^{t_f}\frac{dx}{dt}dt=\int_{t_{in}}^{t_f}\int_{t_{in}}^{t_f} M\frac{d^3x}{dt^3}dt= \qquad (9)$$

$$=M\int_{t_{in}}^{t_f}\int_{t_{in}}^{t_f} j(t)dt,$$

here $j(t)=\frac{d^3x}{dt^3}$ – a jerk made by the vehicle in time [5, 6].

2.3. In general, the cable pulling force T is defined

$$T=\sigma S\ , \qquad (10)$$

here σ– is the mechanical tensile stress of the cable material, N/mm^2.

The value σ is determined by the characteristic of the material forming the research set.

The expression (10) can be written taking into account the relative elongation of the cable:

$$T=E\varepsilon S=E\frac{\Delta l}{l}S\ . \qquad (11)$$

Here E – Jung's module; ε – the relative elongation of the cable.

2.4. If a cable with a length l has an absolute elongation Δl , then its relative elongation is equal to

$$\varepsilon=\Delta l/l \qquad (12)$$

A cable made of synthetic material, when deformed, has an elongation

$$\Delta l=l\left(\sqrt{\frac{l_m}{aT_b}}-\sqrt{\frac{T}{aT_b}}\right), \qquad (13)$$

here l – cable-rope length; T_m – the maximum allowable tension in the cable-rope; T – the working load of the cable-rope; T_b – breaking strength of the cable rope; a – dimensionless coefficient depending on the material and construction of the rope [3, 7, 8].

Aramid fibers have different trade names. The values of the coefficient a are presented in table 1

Table 1 – **Values of coefficient *a***

Type of rope	Polymer name	Coefficient value *a*
Braided eight stranded	Polyamide	3,5
	Polypropylene	11
	Polyester	11
Twisted eight-strand	Polyamide	2,8
	Polypropylene	8
	Polyester	7,5

3. Use of aramid fibers in the production of cable ropes and dynamic slings for towing and pulling of vehicles. In the authors' opinion, researches of various technologies of aramid fibers additional treatment with usage of high-molecular hydrocarbons can be considered perspective.

Thus, analysis of strength and service properties of aramid fibers opens the way to improvement of manufacturing technology of cable ropes and dynamic slings for pulling and towing of WTVs.

Aramid fibers form a completely new and separate category of organic fibers. Fibers in this category have the highest tensile strength and modulus of elasticity as measured by their ratio of strength to density. They are resistant to most common organic solvents, combustibles and lubricants.

When exposed to very strong acids and alkalis, its strength decreases, but it has greater resistance to corrosive factors like salt water. The authors analyzed existing technology for the production of aramid fibers, their strengths and weaknesses, and formed a research polygon with regard to the peculiarities of the operation of wheeled and tracked vehicles.

Particular attention should be paid to the harmful effects of ultraviolet light, atmospheric phenomena and lubricating contaminants. It is found out that necessary breaking force of aramid cable-rope is provided by less number of threads in accordance with high tensile strength. Moreover, the weight of a cable made of aramid fiber is estimated to be 5 to 6 times less than the weight of steel fiber, which is crucial for the actions of the vehicle crew.

However, for aramid fibers, the most aggressive substances are those in contaminated air. It follows that active ultraviolet light and atmospheric precipitation will have a negative effect on the performance characteristics of the cable ropes. To mitigate such impact, cable-rope production technology requires improvements in terms of acquisition of certain properties of chemical fibers or additional treatment of fibers produced by existing technologies. For this purpose the authors have analyzed physicochemical peculiarities and mechanism of formation of web fibers.

The main differences in the process of their formation include enzymatic biosynthesis by matrix block-copolypeptide with a given sequence of amino acid residues; the formation of fibroin filaments occurs at high speed by crystallization oriented in the axial mechanical field; the process of polypeptide synthesis and filament formation can be considered as isothermal [9-13].

Conclusions

The main roads and ground characteristics that determine the vehicles. evacuation conditions are the following: the type of road or ground, their possibility depending on the season and precipitation, the presence of ascents and descents, as well as the nature of road (ground) interaction with caterpillars determined by resistance coefficients. movement and traction.

The mathematical model of pulling a wheeled and tracked vehicle using cable ropes and dynamic can be presented as a system of equations: the jerk carried out by the machine in time reflected third-order differential equation, assuming that all the energy accumulated by the cable is numerically equal to the work of moving stuck machine, corresponds to the equality of the corresponding integrals; the properties of aramid fibers that affect the strength and performance characteristics of cable ropes can be formally expressed through the elongation of the cable.

Analysis of strength and service properties of aramid fibers opens the way to improvement of manufacturing technology of cable ropes and dynamic slings for pulling and towing of WTVs.

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Математичне та фізичне підґрунтя для розроблення симулятора витягування і буксування колісних та гусеничних машин

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Анотація. Предметом вивчення статті є витягування і буксування колісних та гусеничних машин із застосуванням кабель-тросів та динамічних строп. **Метою дослідження** є визначення математичного та фізичного підґрунтя для розроблення симулятора буксирування і витягування колісних та гусеничних машин для дослідження можливості використання арамідних волокон кабель-тросів та динамічних строп. **Завдання дослідження:** На основі аналізу основних характеристик доріг і ґрунтів формалізувати перелік розрахункових параметрів та фізичних величин, що визначають обсяг евакуаційних робіт при витягуванні, буксируванні і транспортуванні колісних та гусеничних машин. Скласти математичну модель, що описує процес витягування та буксирування колісних та гусеничних машин із застосуванням кабель-тросів та динамічних строп. **Отримані такі результати.** Шляхом аналізу основних характеристик доріг і ґрунтів отриманий формалізований перелік розрахункових параметрів та фізичних величин, що визначають обсяг евакуаційних робіт при витягуванні, буксируванні і транспортуванні колісних та гусеничних машин. Математична модель, описує процес витягування та буксирування колісних та гусеничних машин із застосуванням кабель-тросів та динамічних строп складена як система рівнянь. Проаналізовані існуючі технології виробництва арамідних волокон, їх переваги та недоліки, та сформований полігон досліджень з огляду на особливості колісних та гусеничних машин. **Висновки**. Основними характеристиками доріг і ґрунтів, які визначають умови евакуації машин, є вид дороги або ґрунту, їх прохідність в залежності від пори року і атмосферних опадів, наявність підйомів і спусків, а також характер взаємодії дороги (ґрунту) з гусеницями машини, що визначається коефіцієнтами опору руху і зчеплення. Математична модель витягування колісних та гусеничних машин із застосуванням кабель-тросів та динамічних може бути подана як система рівнянь. Аналіз міцностних та експлуатаційних властивостей арамідних волокон відкриває шлях до удосконалення технології виготовленні кабель-тросів та динамічних строп для буксування і витягування колісних та гусеничних машин.

Ключові слова: витягування та буксування колісної та гусеничної техніки; кабель-троси та динамічні стропи; експлуатаційні характеристики арамідних волокон; математична модель витягування колісної та гусеничної техніки.

Математические и физические основы для разработки симулятора вытягивания и буксирования колесных и гусенических машин

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Аннотация. Предметом изучения в статье является извлечение и буксование колесных и гусеничных машин с применением кабелей-тросов и динамических строп. **Целью исследования** является определение математической и физической основы для разработки симулятора буксировки и извлечения колесных и гусеничных машин для исследования возможности использования арамидных волокон кабель-тросов и динамических строп. **Задачи исследования**: на основе анализа основных характеристик дорог и грунтов формализовать перечень расчетных параметров и физических величин, определяющих объем эвакуационных работ при извлечении, буксировке и транспортировке колесных и гусеничных машин. Составить математическую модель, описывающую процесс извлечения и буксировки колесных и гусеничных машин с применением кабель-тросов и динамических строп. **Получены следующие результаты**. Путем анализа основных характеристик дорог и грунтов получен формализованный перечень расчетных параметров и физических величин, определяющих объем эвакуационных работ при извлечении, буксировке и транспортировке колесных и гусеничных машин. Математическая модель, описывающая процесс извлечения и буксировки колесных и гусеничных машин с применением кабель-тросов и динамических строп, составлена как система уравнений. Проанализированы существующие технологии производства арамидных волокон, их преимущества и недостатки и сформирован полигон исследований с учетом особенностей колесных и гусеничных машин. **Выводы**. Основными характеристиками дорог и грунтов, определяющих условия эвакуации машин, являются вид дороги или грунта, их проходимость в зависимости от времени года и атмосферных осадков, наличие подъемов и спусков, а также характер взаимодействия дороги (почвы) с гусеницами машины, определяемый коэффициентами сопротивления движения и сцепления. Математическая модель вытягивания колесных и гусеничных машин с применением кабель-тросов и динамических может быть представлена как система уравнений. Анализ прочностных и эксплуатационных свойств арамидных волокон открывает путь к усовершенствованию технологии изготовления кабель-тросов и динамических строп для буксования и извлечения колесных и гусеничных машин.

Ключевые слова: вытягивание и буксование колесной и гусеничной техники; кабель-тросы и динамические стропы; эксплуатационные характеристики арамидных волокон; математическая модель извлечения колесной и гусеничной техники.