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DEVELOPMENT OF AN ADVANCED DESIGN OF A WORKING TOOL FOR ICE REMOVAL ON ROADS AND SIDEWALKS

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Abstract. Icebreaker machines are essential for maintaining safe and efficient transportation during winter, particularly in regions prone to severe snowfall and ice accumulation. These machines are deployed across railways, highways, and waterways to remove snow and ice, ensuring uninterrupted traffic flow and minimizing accidents. This study examines existing designs of icebreaker machines, analyzing their strengths and limitations. Examples include the Raiko, Vicon, and Karey KL 300 ZPB icebreakers, each employing unique mechanisms such as rotating drums, hydraulic systems, and vibration-based impacts. To address identified shortcomings, this research proposes an improved icebreaker design based on a planetary gear system. The design incorporates a drum with spherical impactors, delivering enhanced ice-breaking efficiency while minimizing road surface damage. Geometric and kinematic parameters are derived, and a mathematical model of ice destruction is presented. Computational experiments analyze factors such as drum rotation speed, impactor diameter, and stress distribution. Results demonstrate the proposed design's ability to generate sufficient destructive stress for effective ice removal, contributing to safer and more reliable winter transport infrastructure.

Keywords: icebreaking machine, working organ, impact element, planetary gear, ice destruction.

Introduction. Icebreaker machines play a crucial role in ensuring the safety and continuous operation of transport systems during the winter period [1]. Their operation is particularly important on railways, sea and river routes, as well as on highways during heavy snowfall and severe frosts. These machines are designed to remove ice and snow from roads, ensuring the safe movement of vehicles and preventing accidents. Modern icebreaker machines feature high technical specifications, innovative technologies, and high operational efficiency, making them indispensable tools in extreme climatic conditions [2-5].

In winter, adverse weather conditions, especially the accumulation of snow and ice, complicate the functioning of transport systems. Icebreaker machines are essential technical tools for ensuring the safety of vehicle movement in such conditions. These machines effectively and quickly remove ice and snow from roads, facilitate the passage of vehicles, and help prevent accidents and delays. Icebreaking equipment used on railways, highways, sea, and river routes has become an integral part of modern transport infrastructure [6].

The impact of snow and ice on roads and vehicle movement during the winter period is significant. As a result, icebreaker machines have become a vital element of transport infrastructure. They clear roads, railways, and sea routes of snow and ice, ensuring the safety of vehicles. The efficient operation of such equipment not only keeps roads usable throughout the year but also contributes to the prevention of emergency situations [7-15].

At this stage of the study, we analyze the existing designs of icebreaker machines.

Currently, there are many different types of designs for icebreaker machines available on the market. For example, in Fig. 1, the design of the Raiko icebreaker machine is shown.

Figure 1 - Raiko Icebreaker Machine

The operation of this device involves the free rotation of a drum with cutters or rods on a road surface covered with an ice layer or compacted snow. The drum's contact with the road is accompanied by pressure or impact, resulting in the complete fragmentation and disintegration of the ice masses. Afterward, the surface of the road becomes smooth and rough.

The design of the icebreaker is such that the working drum does not damage the upper layer of the road. This is achieved through the flexible connection of all the parts and components of the device, as well as proper adjustment of the processing depth. Some models of icebreakers are capable of removing a 50 mm thick ice layer with a processing width of up to 3 meters.

The advantage of this design lies in the ability to apply a pinpoint effect on the ice surface, thanks to the elongated shape of the cutter. The downside of this design is the difficulty of providing sufficient impact force for effective ice breaking, as well as the potential risk of road surface damage when the ice is shattered.

The next version of the icebreaker design is the one developed by Vicon (Fig. 2).

Figure 2 - Vicon Icebreaker

The icebreaker monitors the road surface using both mechanical and hydraulic methods—during the icebreaking process, it keeps track of the road surface, which ensures excellent icebreaking performance.

The technical specifications of the "Vicon" icebreaker are provided in Table 1.

Table 1 - Technical Specifications of the "Vicon" Icebreaker

Parameter Name	Value
Thickness of the cleaned area	50 mm
Width of the cleaned area	2500 mm
Icebreaking speed	5-15 km/h

Hydraulic power supply voltage	24V, constant flow
Diameter of the icebreaking roller	516 mm
Weight	1200 kg
Knife model	122×106

The distinctive feature of this icebreaker design is that the impacts are made in a rectangular shape. However, in this case, the pinpoint effect on the ice is not achieved, which leads to a decrease in the efficiency of the ice removal process.

The next icebreaker design is presented by Karey KL 300 ZPB. This icebreaker is intended for clearing ice and snow from asphalt, concrete, and other road surfaces at airports, airfield runways, federal and local highways, as well as urban areas.

The technical specifications of the Karey KL 300 ZPB icebreaker are provided in Table 2.

Table 2 - Technical Specifications of the Karey KL 300 ZPB Icebreaker

Parameter Name	Value
Type of Mounted Loader	30-50 (lifting capacity 3-5 tons)
Ice Removal Thickness	0.2-8.0 mm
Working Block Action Principle	Vibration, impact

The chassis of the KL 300 ZPB icebreaker can be mounted on any loader with a lifting capacity between 3 and 5 tons.

The main advantage of this type of snow removal equipment is its ability to effectively tackle even the most compact snow formations in both large open areas and confined spaces, all while avoiding damage to the road surface and quickly removing ice and compacted snow.

Another design of the icebreaker machine is shown in Fig. 3**.**

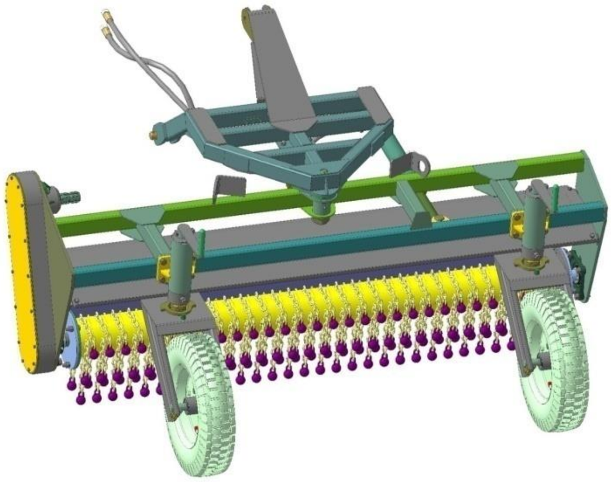

Figure 3 - Construction of Spherical-Shaped Impactors

The distinctive feature of this design is the spherical shape of the impactors. The spherical shape of the impactors allows for targeted action on the ice while preventing damage to the road surface. The disadvantage of this design is the difficulty in achieving sufficiently high impact force values, which prevents complete ice disintegration.

Thus, based on the analysis of existing icebreaker machine designs, the direction for improving their construction to increase the force exerted on the ice layer by the working organ can be identified.

In this article, the authors propose a new design for the working organ of the icebreaker machine. The design of the proposed icebreaker is shown in Fig. 4**.**

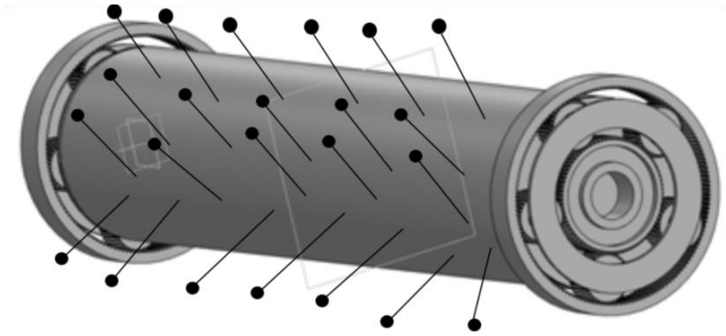

Figure 4 - Proposed Design of the Icebreaker's Working Organ

As shown in Fig. 4, the icebreaker consists of the following main elements: a drum, rods with spherical impactors attached to them, sun gears, satellites, a ring gear, and a carrier. This design is installed on the front linkage mechanism of a wheeled tractor or a front loader.

The working principle of the icebreaker is as follows. By using the drive, the ring gears rotate. As the teeth of the ring gear interact with the satellites, the satellites move relative to their axis and the center of the ring gears. Due to the difference in the diameters of the ring gears and satellites, the movement speed of the satellites increases relative to the center of the main gears. The rapid movement of the satellites leads to the accelerated movement of the carrier, which is connected to the satellites. According to the design, the carrier is directly connected to the drum, to which the spherical impactors are attached. As a result, when the impactors interact with the ice surface, the destruction of the ice is carried out with high efficiency.

Materials and methods. The next stage of the dissertation research involves determining the geometric and kinematic parameters of the proposed icebreaker design, developing a mathematical model for ice removal based on the influence of the working parts, conducting experimental studies on ice removal, and assessing the economic efficiency of the proposed design.

Considering that the proposed icebreaker element is based on the working principle of a planetary gear system, we will select the number of teeth for the gears and satellites. The number of teeth on the sun gear is determined under the condition that the teeth do not intersect with the gear shaft: $z_1 \geq 17$. The following parameters are obtained: z_1: $z_1 = 24$, $H \leq 350$ HB, $z_1 = 21$, $H \leq 52$ HRC, $z_1 = 17$, $H > 52$.

Based on this, we can determine the number of teeth on the sun gear: $z_1 = 24$.

The number of teeth on the ring gear is determined using the following formula:

$$z_3 = z_1 \cdot (i - 1) \quad (1)$$

According to the Eq. (1):

$$z_3 = 24 \cdot (10 - 1) = 216$$

The number of teeth on the satellites is determined by the coaxiality condition, according to which the distance between the tooth pairs with external and internal gears must be equal.

$$a_w = \frac{1}{2} \cdot (d_1 + d_2) = \frac{1}{2} \cdot (d_3 - d_2), \quad (2)$$

In Eq. (2), $d = mz$ refer to the diameters of the pitch circles of the gears.

Taking into account the formula for determining the diameters of the pitch circles of the gears, the alignment condition will be as follows:

$$a_w = \frac{1}{2} \cdot (mz_1 + mz_2) = \frac{1}{2} \cdot (mz_3 - mz_2) \quad (3)$$

Since the planetary gear modules are the same, Eq. (1) takes the following form:

$$z_2 = \frac{1}{2} \cdot (z_3 - z_1) \quad (4)$$

$$z_2 = \frac{1}{2} \cdot (216 - 24) = 96$$

The number of teeth obtained is checked according to the assembly and clearance conditions. The assembly condition requires that the teeth of the gears align with the gaps in the satellites at all connections, otherwise, it will be impossible to assemble the gear set. With the symmetrical arrangement of the satellites, it has been determined that the assembly condition is satisfied when the sum $(z_1 + z_3)$ of the teeth on the sun gears is a multiple of the number of satellites $c = 2...6$. That is, the following condition must be met:

$$\frac{(z_1 + z_3)}{c} = Z$$

$$\frac{(24 + 216)}{5} = 48$$

The clearance condition requires that the teeth of the satellites do not make contact with each other. To ensure this, the sum $d_a = m(z_2 + 2)$ of the radii of the peaks of the neighboring satellites' teeth must be smaller than the distance between their axes. That is, the following condition must be met:

$$d_{a2} < l = 2a_w \sin\left(\frac{\pi}{c}\right) \quad (5)$$

In Eq. (5), $a_w = 0{,}5m(z_1 + z_2)$ is central distance.

$$d_{a2} = 0{,}5 \cdot 1{,}5 \cdot (216 + 96) < l = 2 \cdot 1{,}5 \cdot (216 + 2)\sin\left(\frac{\pi}{5}\right) \quad (6)$$

$$d_{a2} = 0{,}5 \cdot 1{,}5 \cdot (216 + 96) < l = 2 \cdot 1{,}5 \cdot (216 + 2)\sin\left(\frac{\pi}{5}\right) \quad (7)$$

$$d_{a2} = 234 < l = 384{,}41$$

Let's determine the diameter of the sun gear:

$d_1 = mz_1 = 1{,}5 \cdot 17 = 26$ mm

Let's determine the diameter of the ring gear:

$d_3 = mz_3 = 1{,}5 \cdot 216 = 324$ mm

Let's determine the diameter of the satellite:

$d_2 = mz_2 = 1{,}5 \cdot 96 = 144$ mm

Based on the geometric parameters of the experimental models, the diameter and length of the drum are assumed to be $d_b = 298$ mm and $l_b = 2500$ mm, respectively. Thus, the icebreaker working organ is represented with the following geometric parameters (Table 3).

Table 3 – Geometric Parameters of the Icebreaker Working Organ

Table 3 – Geometric Parameters of the Icebreaker Working Organ

Parameter Name	Symbol	Value
Number of teeth on the sun gear	z_1	24
Number of teeth on the ring gear	z_3	216
Number of teeth on the satellites	z_2	96
Diameter of the sun gear	d_1	36 mm
Diameter of the ring gear	d_3	324 mm
Diameter of the satellite	d_2	144 mm
Diameter of the drum	$d_{б}$	298 mm
Length of the drum	$l_{б}$	2500 mm
Diameter of the spherical impactor	$d_{сб}$	25 mm
Distance from the rotation axis to the impactor	a_w	350 mm

Thus, the geometric characteristics of the icebreaker working organ have been determined. The problem under consideration is a special case of the mechanical problem of strongly deformable bodies, described by a nonlinear constructive equation [16], where two spheres, moving along an axis connecting their centers with velocities v1v_1 and v2v_2, collide [17]. In this case, one of the bodies is a stationary elastic half-space with zero curvature at the boundary z=0z = 0, while the other body, with a weight GG and a collision radius RR, has a non-deformable spherical surface (Fig. 3). The solution for an infinite homogeneous half-space [17, 18] is based on the work of G. Hertz [19], which allows deriving the law of collision for bodies of any shape by combining the static compression in the body parts at the contact point with the general equations of motion for other parts of the bodies.

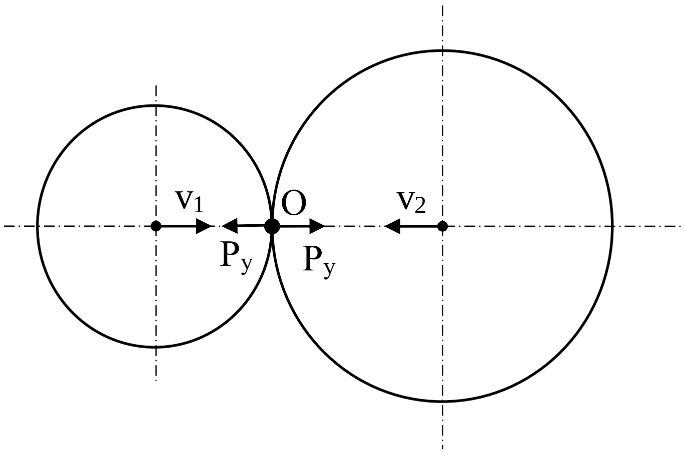

Figure 5 – Classical Diagram of Elastic Deformable Sphere Collision According to Hertz [18]

After transformations of the formula, we obtain the dependencies for determining the mass mm of the impactor and its collision velocity with the ice:

$$m = \frac{3888 \cdot (1-\mu^2)^4 \cdot R^3 \cdot \pi^5 \cdot [\sigma]^5}{480 \cdot E^4 \cdot v_0^2 \cdot (1-2\cdot\mu)^5}, \text{ кг}, \quad (16)$$

$$v_0 = \sqrt{\frac{3888 \cdot (1-\mu^2)^4 \cdot R^3 \cdot \pi^5 \cdot [\sigma]^5}{480 \cdot E^4 \cdot m \cdot (1-2\cdot\mu)^5}}, \text{ м/с} \quad (17)$$

In Eqs. (16) and (17), [σ] represents the allowable stress for ice fracture, in Pascals (Pa). For the computational experiment, we select the following ranges of parameter changes:

1. The rotation speed of the icebreaker drum;
2. The diameter of the spherical impactor.

The computational experiment will be carried out with the following initial data:

Table 4 – Physical and Mechanical Properties of Ice

Параметр аты	Белгі	Параметр мәні
Мұздың Пуассон қатынасы	μ	0,33
Мұздың серпімділік модулі	E	$2{,}8 \cdot 10^{10}$ Па
Сфералық соққының диаметрі	$d_{сб}$	5; 10; 15; 20 мм
Сфералық соққының салмағы	$m_{сб}$	0,51 кг; 4,08 кг; 16,72 кг; 32,66 кг
Барабан жылдамдығы	$n_{б}$	116...1160 айн/мин

To remove ice of a certain thickness, a specific amount of destructive stress needs to be generated in the ice, specifically at the edge of the contact area, with a minimum of 66 MPa or at least 99 MPa in the center of the contact area.

Results and discussion. Let's determine the numerical dependence of the stress at the edge of the contact area on the rotation speed of the drum, for a spherical impactor with a diameter of 5 mm and an impact weight of 0.51 kg.

The calculation results are presented in Table 5.

Table 5 – Numerical Dependence of Stress at the Edge of the Contact Area on the Drum Rotation Speed for a Spherical Impactor with a Diameter of 5 mm and an Impact Weight of 0.51 kg

Drum rotation speed, RPM	Impact speed of the impacter with the ice, m/s	Stress value at the center, MPa
116	4,85	31,59
166	6,95	36,46
216	9,05	40,51
266	11,14	44,03
316	13,24	47,17
366	15,33	50,02
416	17,42	52,66
466	19,52	54,48
516	21,61	57,19
566	23,71	59,11
616	25,8	61,71
666	27,89	63,91
716	29,99	66,96
766	32,09	69,61
816	34,18	71,46
866	36,27	74,49
916	38,37	76,25
966	40,46	78,16
1016	42,55	81,79
1066	44,65	84,19

1160	48,59	86,76

The graphical explanation of the dependence of the stress created in the ice on the drum rotation speed is shown in Fig. 6.

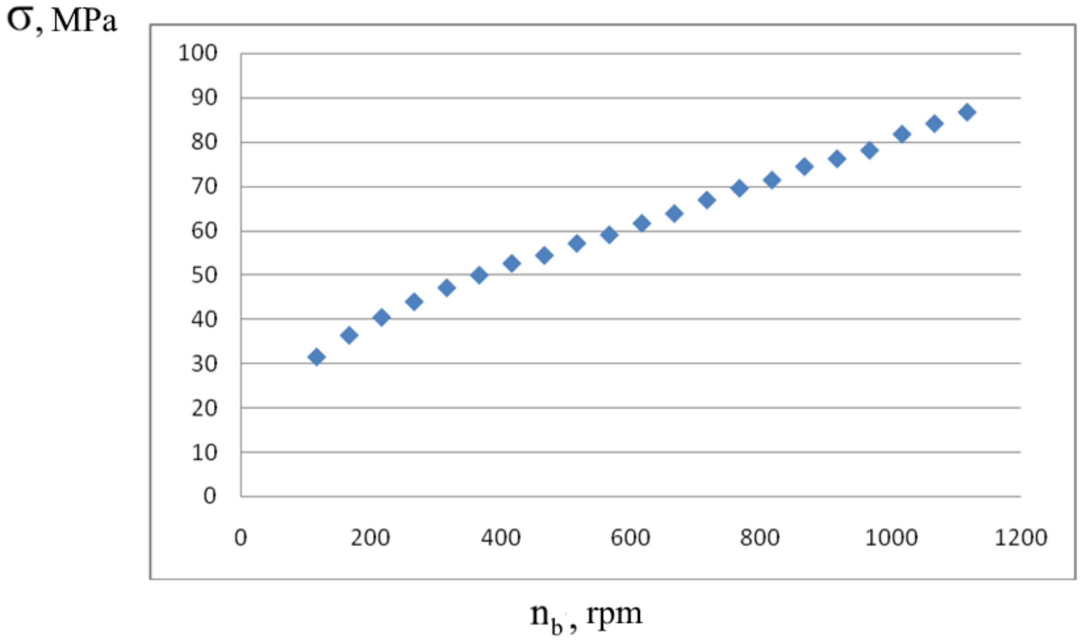

Figure 6 – Graphical Explanation of the Dependence of Stress Created in the Ice on the Drum Rotation Speed

Now, let's determine the dependence of the spherical impactor's collision speed with the ice on the thickness of the ice.

Table 6 – Dependence of the Spherical Impactor's Collision Speed with Ice on the Thickness of the Ice

Ice thickness, mm	Impact speed of the impacter with the ice, m/s	Drum rotation speed, RPM
5	0,30	11,89
10	0,70	28,3
15	1,17	46,98
20	1,67	67,31
25	2,21	88,97
30	2,78	111,74
35	3,37	135,49

The graph of the drum rotation speed with respect to ice thickness is shown in the Fig.

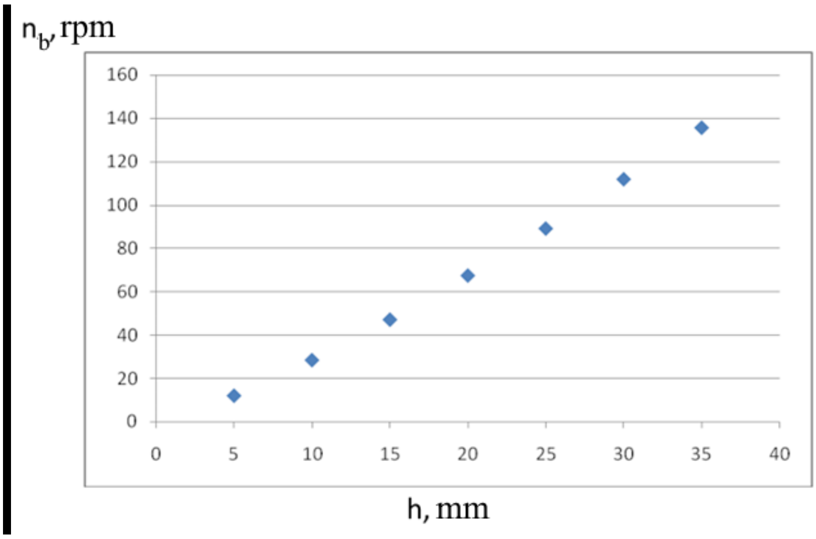

Figure 7 – Graph of Drum Rotation Speed with Respect to Ice Thickness

Conclusion. Thus, the analysis of modern ice-breaking machine designs has been carried out, with an emphasis on their strengths and weaknesses. Based on the analysis, an improvement to the working mechanism of the ice-breaking machine has been proposed, based on the principle of planetary gear transmission. The geometric and kinematic characteristics of the new design are described, a mathematical model of ice destruction is presented, as well as the results of computational experiments. The main goal of the development is to enhance the efficiency of ice destruction, minimize damage to the road surface, and improve the operational qualities of the ice-breaking equipment.

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ЖОЛДАҒЫ ЖӘНЕ ЖОЛДАҒЫ МҰЗДЫ ЖҰРУ ҮШІН ЖҰМЫС ОРГАНЫНЫҢ ЖЕТІЛДІРІЛГЕН КОНСТРУКЦИЯСЫН ӘЗІРЛЕУ

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Аңдатпа. Мұзжарғыш машиналар қыстың қатал жағдайларында көлік қозғалысының қауіпсіздігі мен тиімділігін қамтамасыз етуде маңызды рөл атқарады. Бұл машиналар қар мен мұзды теміржолдардан, автомобиль жолдарынан және су жолдарынан тазалап, көлік ағынын үздіксіз қамтамасыз етіп, апаттардың алдын алады. Бұл зерттеу мұзжарғыш машиналардың қолданыстағы құрылымдарын талдап, олардың артықшылықтары мен кемшіліктерін анықтайды. Мысал ретінде Raiko, Vicon және Karey KL 300 ZPB мұзжарғыштары қарастырылады, олардың әрқайсысы айналмалы барабандар, гидравликалық жүйелер және тербеліс негізіндегі соққы механизмдерін қолданады. Анықталған кемшіліктерді шешу үшін зерттеуде планетарлық беріліс жүйесіне негізделген жетілдірілген мұзжарғыш құрылымы ұсынылады. Жобада барабанға бекітілген сфералық соққылар пайдаланылады, бұл мұзды тиімдірек бұзуға және жол бетіне зақым келтіруді азайтуға мүмкіндік береді. Геометриялық және кинематикалық параметрлер анықталып, мұзды бұзу процестерінің математикалық моделі ұсынылды. Есептік эксперименттер барабанның айналу жылдамдығы, соққы диаметрі және кернеудің таралуы сияқты факторларды талдайды. Нәтижелер ұсынылған дизайнның мұзды тиімді жою үшін қажетті кернеуді қамтамасыз ете алатынын көрсетіп, қыста көлік инфрақұрылымының қауіпсіздігі мен сенімділігін арттыруға үлес қосатынын дәлелдейді.

Түйін сөздер: мұзжарғыш машина, жұмыс органы, соққы элементі, планетарлық беріліс, мұзды бұзу.

РАЗРАБОТКА УСОВЕРШЕНСТВОВАННОЙ КОНСТРУКЦИИ РАБОЧЕГО ОРГАНА ДЛЯ РАЗРУШЕНИЯ ЛЬДА НА ДОРОГАХ И ТРОТУАРАХ

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Аннотация. Машины для разрушения льда играют важную роль в обеспечении безопасности и эффективности транспортной системы в зимний период, особенно в условиях сильного снегопада и обледенения. Эти машины используются для очистки железных дорог, автомобильных и водных путей от снега и льда, что позволяет поддерживать бесперебойное движение транспорта и предотвращать аварии. В данном исследовании проанализированы существующие конструкции ледоскалывающих машин, выявлены их сильные и слабые стороны. Примеры включают машины Raiko, Vicon и Karey KL 300 ZPB, каждая из которых использует уникальные механизмы, такие как вращающиеся барабаны, гидравлические системы и вибрационно-ударные технологии. Для устранения выявленных недостатков предложена усовершенствованная конструкция машины для разрушения льда, основанная на принципе планетарной зубчатой передачи. Конструкция включает барабан со сферическими ударными элементами, что обеспечивает более эффективное разрушение льда при минимальном повреждении дорожного покрытия. Определены геометрические и кинематические параметры, разработана математическая модель процесса разрушения льда. В рамках вычислительных экспериментов проанализированы такие факторы, как скорость вращения барабана, диаметр ударного элемента и распределение напряжений. Результаты показывают, что предложенная конструкция способна создавать достаточное напряжение для эффективного разрушения льда, способствуя повышению безопасности и надежности транспортной инфраструктуры в зимний период.

Ключевые слова: ледоскалывающая машина, рабочий орган, боек, планетарная передача, разрушение льда