DEVELOPMENT AND RESEARCH OF WORKING PARTS OF JOINT CUTTING MACHINES WITH CYCLOIDAL MOTION

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Resume

The development of a country's economy largely depends on the pace and efficiency of construction work, which, in turn, is determined by the extent to which innovative technologies and techniques are used. This work is devoted to justification of the basic parameters and the development of a new working body for a machine for cutting joints in road surfaces. A design with cycloidal motion is proposed, which intensifies the destruction process due to the vibrational impact of the cutters on the material being processed. The use of such a working body provides a vibrational effect, increases the cutting speed, and reduces the energy consumption of the process. As a result of intensifying the interaction between the working body and the material, it was possible to reduce the energy consumption of cutting by 1.13 times, and increase productivity by 1.18 times compared to analogues.

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1 Introduction

In Kazakhstan, a number of important tasks related to creation of new and highly productive equipment, and the modernization of existing technical means in road construction, are to be solved in the shortest possible time to improve the quality of work in the construction and repair of motorways. The mechanization of the construction, repair, and reconstruction of urban and road facilities is linked to the implementation of measures to reduce the energy and material costs of their implementation, which requires new, high-performance, and less energy-intensive equipment [1-3].

In this regard, the great importance is devoted to machines designed for cutting joints in road surfaces. The main disadvantages of existing machines are: low productivity and reliability of the machine's working body, high energy consumption, and significant dimensions and weight of the working body. Based on an analysis of scientific and technical literature [2-4], it has been established that existing joint cutting machines are inefficient, have high energy consumption, and low reliability of chain working parts. According to the analysis of existing machine designs and theoretical and experimental studies of soil cutting processes, it has been established that existing cutter machines have practically exhausted their potential for further productivity improvements, creating a need for more efficient, high-performance, and less energy-intensive cutter machines.

The main idea of this work was to use the principle of cycloidal motion to cut slots in road surfaces, which allows for more intense interaction between the working body and the material being processed. In addition, the working bodies of the slot cutting machine are made according to mutually enveloping cycloidal curves, which allow for the minimum possible specific energy consumption of the working process.

The cycloidal (planetary-rotary) motion of the working parts of machines significantly reduces their weight and dimensions and expands their technological capabilities. A positive feature of machines with cycloidal motion of working parts is that they can operate at speeds significantly exceeding those calculated for traditional machines [5-7].

It is precisely in these areas that the development of a new design for a road cutting machine with cycloidal movement of the working body is justified. This machine design makes it possible to intensify the process of road surface destruction by means of the vibrational impact of the cutters on the material being worked on, reduce the energy intensity of the cutting process, and expand the technological capabilities of the machine. Thus, the justification of the parameters and development of the working body of the machine for cutting joints is a very urgent task aimed at finding and creating new innovative technology [4].

The subject matter of this study is directly related to the field of "Mechanical Engineering in the Transport Industry" and the development of the automotive industry, since the design solutions considered in this work relate to the creation and improvement of working parts for road construction machines used in the formation and restoration of transport infrastructure. The proposed design and kinematic solutions are aimed at improving the efficiency of equipment operation, reducing energy consumption, and increasing the productivity of machines used in transport construction. Thus, the results of the work are directly relevant to the development of transport engineering, in particular to the improvement of technological equipment for the automotive industry, ensuring the improvement of road surfaces and the reliability of transport communications.

An analysis of existing road-cutting machine designs has shown that their main drawbacks - low productivity, insufficient reliability of working components, and high energy consumption - are due to the fact that the potential of traditional cutting schemes has been exhausted. It has been established that further improvements in the efficiency of road construction equipment require a transition to innovative kinematic solutions capable of intensifying the material destruction process through dynamic forces. Thus, there is a need for research aimed at scientifically substantiating the parameters of a working body with a cycloidal motion type, which would allow for overcoming existing technological limitations and significantly reducing energy consumption.

The objective of this study was to improve the performance of road milling machines by justifying the design parameters and developing an innovative working body with cycloidal motion.

To achieve this goal, the following tasks were addressed:

1. Justifying the application of the cycloidal motion principle to intensify the interaction between the working body and the road surface.
2. Developing a mathematical model of the working body's dynamics and derive equations for determining the cutting force, taking into account vibrational effects.
3. Conducting a comparative analysis of the proposed design's efficiency against existing counterparts (such as the DFM-40, DFM-RMT, etc.) in terms of productivity and specific energy consumption.
4. Experimentally verifying the operational capability of the developed device on a physical model and validate the adequacy of the derived theoretical relationships.

2 Materials and methods

A well-known machine for cutting joints in road pavements comprises a hollow frame with a rectangular cross-section. A drive kinematic transmission in the form of a chain gear transmission, with a chain and drive and driven sprockets, is housed within the frame cavity.

The eccentric shaft comprises a main section and, on either side of it, eccentrically offset sections. The driven sprocket is coaxially aligned and rigidly connected to the main section of the shaft.

Disc cutters are mounted on the eccentrically offset sections of the shaft. They are oriented parallel to each other and perpendicular to the shaft axis. The disc cutters are polygonal in shape with equal convex sides, and removable cutting edges are secured at the vertices of the polygons.

On the sides of the frame facing the cutters, coaxial with the eccentrically offset sections of the eccentric shaft, are attached the planetary gears with an internal gear ring [4-8]. Satellite gears with an external gear ring are located and rigidly attached to the side surfaces of the disc cutters. The external gear ring of the satellite gear meshes with the internal gear ring of the planetary gear.

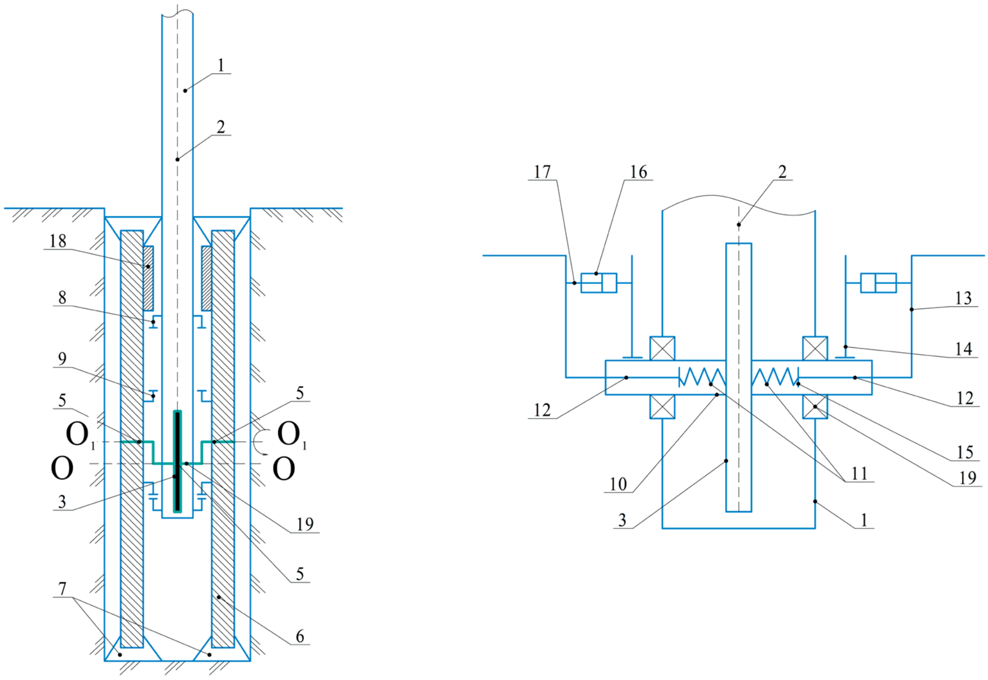
The disadvantages of the known device include limited functionality, namely, the inability to cut joints in road surfaces, dense and frozen soils, and other surfaces with a minimum number of working strokes.

The study is based on a theoretical justification of the main parameters of the working body of machines for cutting joints with cycloidal motion of cutting discs, which intensifies the interaction of the cutting elements of the working body with the material being processed. When analyzing the laws of motion of the working body, the method of interaction of the working body with the material being processed and the trajectory of the working body's motion were taken into account [5-9].

The technical result of using the proposed design is an expansion of functional capabilities, namely, cutting joints of various widths in different surfaces with high quality of their surfaces and high-performance cutting with a minimum number of working strokes.

The eccentric shaft is prefabricated and consists of a prefabricated main section in the form of a cylindrical sleeve with two spring-loaded coaxial main sections of equal length, spring-loaded coaxial main sections of the eccentric shaft, connected by their side edges to eccentrically offset sections of the eccentric shaft, which are synchronously extended in opposite directions from the center of this section. At the same time, the cylindrical sleeve of the main section of the eccentric shaft is rigidly connected with the opening of the driven star by its outer surface. A holder oriented perpendicular to the shaft axis is attached to the outer surface of the sleeve, which is additionally introduced into the drive device for axial displacement of the side edges of the eccentric shaft, for example, in the form of a hydraulic cylinder, the extendable rod of which interacts with the side face of the eccentric shaft with the possibility of synchronous multidirectional extension of its sections and subsequent fixation of the achieved level of extension of the side faces of the eccentric shaft, together with its eccentrically displaced sections, wherein the inner rims of the planetary gear wheels are elongated along the axis by the amount of the drive rod stroke.

The device is mounted on a vehicle, such as a truck, by means of a frame 1 (Figure 1). Rotation is transmitted from the drive to a chain gear consisting of a drive sprocket, chain 2, and driven sprocket 3, and from the driven sprocket 3, rotation is transmitted to the eccentric shaft 4, and from it to the disc cutters 6. At the same time, the inner rims of the planetary gears 8 are in internal meshing with the outer rims of the satellite gears 9 (the wheels 9 roll inside the wheels 8). Disc cutters 6 perform a rotational movement around the axis O_1-O_1 of eccentrically displaced sections 5 of the eccentric shaft. The points of the cutters 7 with the same name move along complex trajectories representing hypotrochoids. Moving along the branches of the hypotrochoid, when in contact with the road surface, the



a) b)

1 - frame | *2 - chain gear transmission with chain*
3 - trailing star | *4 - eccentric shaft with main section*
5 - eccentrically displaced areas | *6 - disc cutters*
7 - removable cutters | *8 - planetary gears with internal gear rim*
9 - satellite gears | *10 - cylindrical bushing*
11 - elastic element | *12 - main section of the eccentric shaft*
13 - side edges | *14 - holder*
15 - washer | *16 - hydraulic cylinder*
17 - sliding rod | *18 - counterweight*
19 - bearing | *O-O - axis of rotation of the main section of the eccentric shaft together with the driven star 3*
O_1-O_1 - rotation axis of disc cutters 6

***Figure 1** Device for cutting joints in road surfaces: a - general view of the device; b - enlarged image of the eccentric shaft* cutters 7 of the cutters 6 make a cut, penetrating the road surface to the full cutting depth. At the same time, the speed of the cutter moving along the hypotrochoid does not remain constant, since its movement from the top to the middle of the hypotrochoid branch is slowed down and, conversely, from the middle of the branch to the next top, it is accelerated, resulting in a vibration-force impact on the road surface. To reduce vibrations on eccentrically offset sections of the shaft, counterweights 18 are used. Their use reduces the wear on the bearings 19 of the eccentric shaft. The cut soil is removed to the road surface by cutters 6.

When it is necessary to automatically increase the cutting width, the microprocessor control device sends a command to activate the drives that axially shift the side edges 13 of the eccentric shaft. Their displacement causes the displacement of elements 11. The achieved position of the drive rods 17 is fixed. After the cutting is complete, under the action of elastic deformations of elements 11, the drive rods 17 return to their initial equilibrium state.

The device is effective in operation and has extended functionality, namely, it allows cutting the joints of different widths with a minimum number of working strokes.

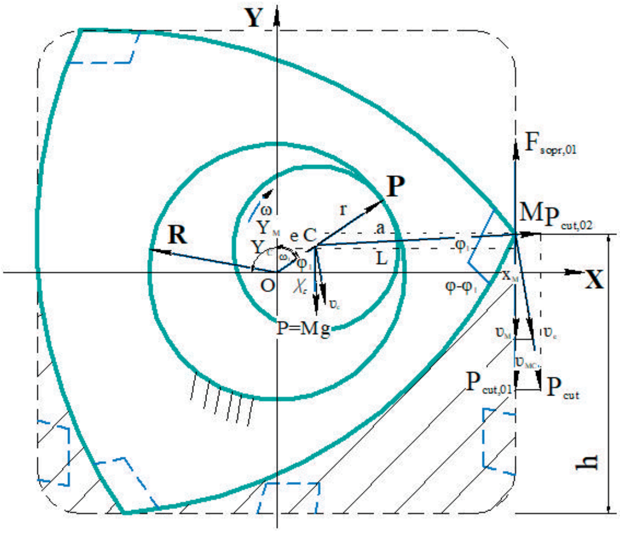
The cross section of the machine's working body is a flat triangular shape, the points of which, when rotating around two parallel axes (O-O, O_1-O_1), describe the curved lines-hypotrochoids with straight branches, and the side generatrices of the sections roll along these branches as if along guides.

To determine the main parameters of the working body, the kinematic diagram of its movement was considered (Figure 2).

The cutting trajectory of the rotary working body with cycloidal motion of the discs is formed as a result of the combination of the translational motion of the machine at a speed of υ_{mash} and the complex rotational motion of the rotor at a speed of ω_r shown by dotted lines in Figure 1. The direction of rotational movement in the lower part of the rotor coincides with the direction of the machine's translational movement, and in the upper part, it is opposite to it.

The coordinates of the cutting path are determined as follows [5-9]:

$$\left.\begin{aligned} x &= \upsilon_{masch}\cdot t - c + e\cdot\cos(\omega_1\cdot t) + a\cdot\cos(\omega\cdot t) \\ z &= -H_{o.p.} + e\cdot\sin(\omega_1\cdot t) + a\cdot\sin(\omega\cdot t) \end{aligned}\right\},(1)$$



CM - distance from the satellite axis to the cutting element

X_m, Y_m - coordinates of point M of the cutting element

φ_1, ω_1 - angle of rotation and angular velocity of the driver

φ, ω - angle of rotation and angular velocity of the satellite

$P^k_{cut,01}$ - tangential component of cutting force P_{rez}, N

$P^n_{cut,02}$ - the normal component of the cutting force is P_{cut}, N

$F^k_{sopr,01}$ - tangential component of total resistance force F_{sopr}, N

υ_{MC} - speed of point M (cutting element of the disc working body) relative to point C of the satellite center

υ_M - absolute speed of point M (cutting element of the disc working body) relative to point O, the center of the wheel shaft

O - wheel hub

C - satellite center

CM = a, OC = e (eccentricity)

R - the radius of the large stationary wheel

r - satellite radius

X_c, Y_c - coordinate points C

h - cutting depth, mm

υ_c - speed of point C relative to point O, the center of the wheel shaft

***Figure 2** Diagram for determining the kinematic parameters and cutting force of a disc-type working body with cycloidal motion* where υ_{masch} - vehicle speed, m/s; t - time spent by the cutting edges of the working tool in the cutting process, s; c - rotor shaft offset, mm; $H_{o.p.}$ - difference between the levels of the machine platform and the axis of rotation of the working body, mm; ω_1 - angular velocity of the driver, rad/s; e - eccentricity, mm; a - distance from the satellite axis to the cutting element, mm.

The cutting force when penetrating the road surface, with certain assumptions, can be determined based on the theorem of kinetic energy of a material point. This theorem is expressed by the equation [5-9]:

$$\frac{J_c \cdot \omega^2}{2} + \frac{M \cdot \upsilon_c^2}{2} = A = P_{cut,01} \cdot L_{cut}\,, \tag{2}$$

where J_c - moment of inertia of rotor and satellite discs, kg·mm^2; υ_c - satellite rotation speed, m/s; A - work expended in cutting the road surface, J; ω - rotor angular velocity, rad/s; L_{cut} - cutting path, mm; $P_{cut,01}$- tangential component of cutting force P_{cut}, N.

After transformations, based on the theorem on the change in kinetic energy, one obtains the cutting force [5-9]:

$$P_{cut,01} = \frac{\left(\frac{M \cdot r^2}{2} + \frac{J_c}{2}\right) \cdot \left[\frac{(R-r)}{r}\right]^2 \cdot \omega_1^2}{L_{rez}}, \tag{3}$$

where R - gear wheel radius, mm; r - satellite radius, mm; ω_1 - angular velocity of the driver, sec^{-1}; M - mass of the disc and the cut road surface, $M = m_{rot} + m_s$, kg.

The tangential component of the cutting force, when the working body is introduced into the road surface, takes the form [5-9]:

$$P_{cut,01} = \frac{\left(\frac{(m_{rot} + F_{cr} \cdot L_{cut} \cdot \gamma) r^2}{2} + \frac{J_c}{2}\right) \cdot \left[\frac{(R-r)}{r}\right]^2 \cdot \omega_1^2}{L_{rez}}, \tag{4}$$

or

$$P_{cut,01} = \frac{\left(\frac{\left(m_{rot} + F_{cr} \cdot \lambda \cdot \gamma \cdot \frac{\sin(\delta+\theta)}{\sin\theta}\right) r^2}{2} + \frac{J_c}{2}\right) \cdot \left[\frac{(R-r)}{r}\right]^2 \cdot \omega_1^2}{L_{rez}}. \tag{5}$$

After transforming Equation (5), taking into account that $P_{cut.01} = 0.85 P_{cut}$, one obtains

$$P_{cut} = \frac{0.06 \cdot \omega_1^2 \left[m_{rot} + F_{cr} \cdot \lambda \cdot \gamma \cdot \frac{\sin(\delta+\theta)}{\sin\theta}\right] \cdot (r^2 + J_c)}{L_{cut}}, \tag{6}$$

where δ - cutting angle, degrees; θ - angle between the chip trajectory and the cutting surface, degrees; λ - length of cut section, mm; F_{cr} - average cross-sectional area of the cut, mm^2; γ - asphalt concrete density, kg/mm^3.

To verify the theoretical dependencies and evaluate the performance, experiments were conducted on a physical model of a disc working body with cycloidal motion (Figure 3). To determine the cutting force, the bending stresses on the rotor shaft were measured using the strain gauges. Using the similarity theory,

Figure 3 *Experimental setup with cycloidal motion of the working body*

Figure 4 *Material cut made by the proposed design*

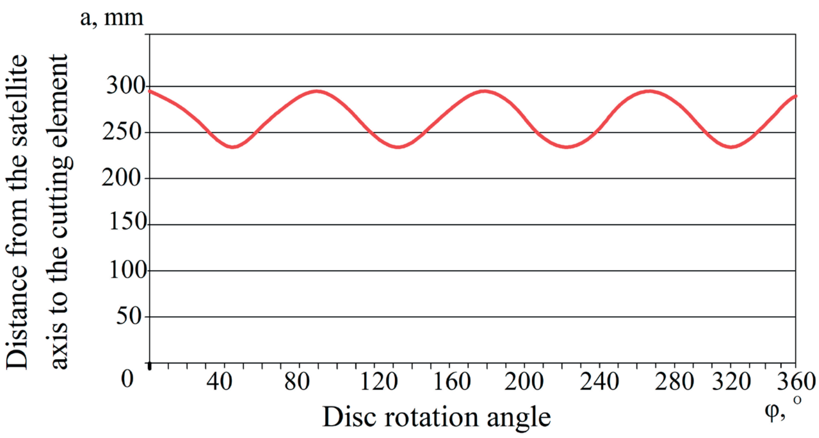


Figure 5 *Graph showing the dependence of CM = a on the satellite's angle of rotation*

the experimental values of the model were converted to full-scale results.

During experimental studies conducted on a physical model, a visual and instrumental analysis was performed on the cross-sections of the asphalt concrete pavement. Unlike the traditional cutting with disc cutters, where the cut surface is smooth, the cut produced by the cycloidal motion of the working body is characterized by the presence of microcracks, indicating that the tensile deformations predominate over shear deformations.

This confirms the hypothesis that the variable speed of the cutters along the hypotrochoid (from a minimum at the start of contact to a maximum during the active fracture phase) creates a "dynamic impact" effect (Figure 4). Zones of cyclic loading are clearly visible on the sample cross-section, which correlate with the calculated cycloid pitch. This fracture mechanism made it possible to achieve a cutting depth of up to 200 mm while significantly reducing the forces on the cutting tool. A comparison of the cut profile showed that the width of the slot remains stable along its entire length, which meets the requirements for expansion joints in road pavements.

3 Results and discussions

The trajectories of the cutting elements are shown in Figures 5 and 6.

Figure 6 shows that the trajectory of the cutters in polar coordinates has the shape of a regular quadrilateral square with smooth transitions at the vertices. When the rotor rotates, the speed of movement on each branch of the trajectory changes from a minimum to a maximum value.

Under the action of the cycloidal cutting force, vibrations are transmitted to the material being cut, which allows additional energy to be supplied, increasing the machine productivity and workflow

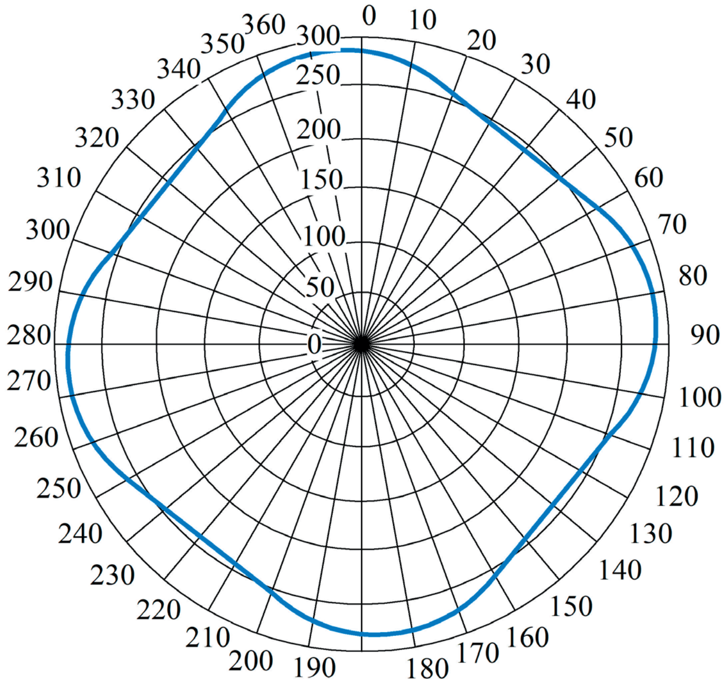


Figure 6 *Trajectory of cutter movement in polar coordinates of a disc-shaped working body with cycloidal movement of cutting elements (degree)*

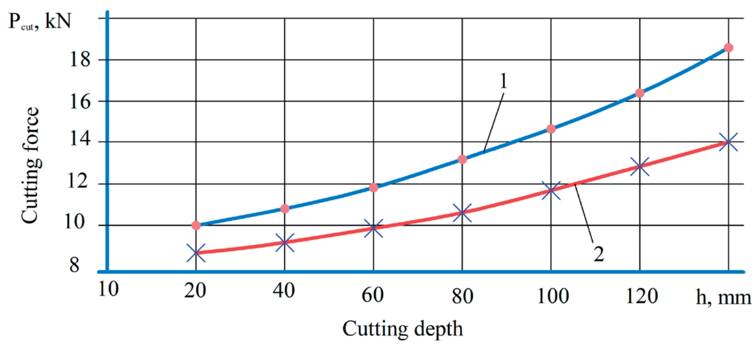


Figure 7 *Dependence of the cutting force on the thickness of the road surface being cut: 1-theoretical; 2-experimental*

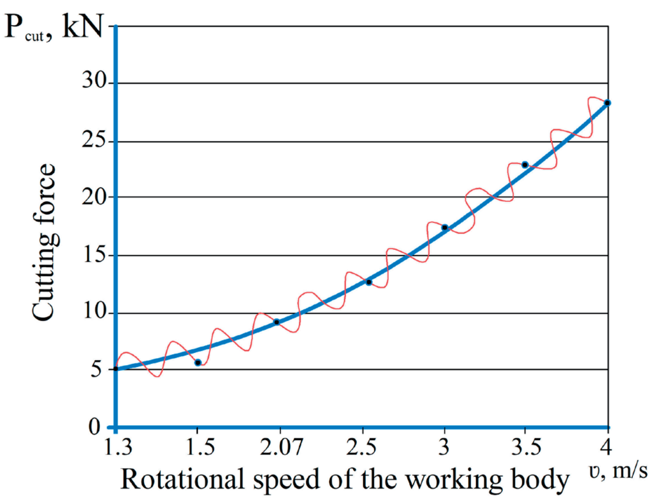


Figure 8 *Dependence of the cutting force on the rotational speed of the disc working body at a cutting width of 15 mm and a cut layer thickness of 140 mm*

Table 1 *Comparative analysis of slitting machines*

No.	Device	Productivity, mm/minutes	Installed capacity, kW	Specific energy consumption, kW-h/m
1	DFM-40	7100	40	5.63
2	DFM-RMT	6500	37	5.69
3	DFM-64	6200	35	5.65
4	New ZRM-1 machine	8700	35	4.02

efficiency. The cycloidal movement of the disc makes it possible to intensify the interaction of the cutting elements with the material being developed.

The results of experimental studies of the dependence of cutting forces on the thickness of the road surface being cut are shown in Figure 7.

Analysis of the experimental results shows that at shallow cutting depths, the discrepancy between the theoretical and experimental cutting force values is small, then increases to 15%, which does not exceed the permissible experimental error limits.

Figure 8 shows a graph of the cutting force dependence on the rotational speed of the disc working body.

The dependence of the cutting force on the rotational speed of the working body has been confirmed experimentally. In all the experiments, the cutting force increased with increasing cutting speed. This pattern can be explained by the specific mechanical conditions of the road surface cutting process, which result from the cyclical change in the speed at which the cutting elements impact the asphalt concrete [10-12].

Analysis of the results obtained reveals the key relationships between the kinematics of motion and the force parameters of the process. It has been established that the nature of the change in cutting force correlates directly with the trajectory of the cutters (hypotrochoid). The change in velocity along each branch of the trajectory, from the minimum to the maximum value, creates the effect of a cyclic dynamic impact [4-6].

The relationship between rotational speed and material resistance is confirmed by the fact that the cycloidal motion generates forced vibrations that are transmitted to the fracture zone. This intensifies the process: the additional kinetic energy of the vibrational impact reduces the static cutting resistance. As experimental data show, at a speed of n=150 rpm, the cutting force is 30 kN, which is 40% lower than that of machines with a bar chain (50 kN) and 33% lower than that of discs with uniform rotation (45 kN) [13-14].

The observed trend of increasing the cutting force with increasing penetration depth (up to a 15% deviation from theory) is explained by the increase in the cross-sectional area of the cut and the density of the asphalt concrete in the contact zone. Nevertheless, it is precisely the use of a cycloidal trajectory that allows for maintaining an advantage in energy efficiency across all tested operating modes, resulting in a 1.13-fold reduction in specific energy consumption compared to mass-produced counterparts such as the DFM-40 and DFM-64.

A comparative analysis of the most common slot cutting machines and the new machine is presented in Table 1.

The results presented in this paper were obtained under certain assumptions. In particular, when developing the mathematical model of the cutting tool's dynamics (Equations (1)-(4)), it was assumed that the cutting process takes place in a homogeneous asphalt concrete medium, without accounting for large foreign inclusions. Experimental studies were conducted on a physical model under laboratory conditions, where the variation of parameters was limited to a range of rotational speeds up to n=150 rpm and a cutting depth of up to h = 200 mm. Furthermore, the assessment of the cutter wear resistance was not considered in this work; the main focus was on the force and energy efficiency of the kinematic scheme.

Further research in this area should focus on studying the effect of various geometric shapes of the cutting segments on the stability of the cycloidal trajectory [15-18]. An important step in the development of this topic will be conducting field tests of a full-scale prototype of the ZRM-1 type road-cutting machine under real road conditions on various types of pavement (cement concrete, reinforced concrete). In addition, of scientific interest is the optimization of vibration modes to minimize the dynamic loads on the base machine's frame, which will further enhance the operational reliability of the proposed design, which has already demonstrated a 1.18-fold performance advantage in current tests.

4 Conclusions

In this study was addressed a pressing scientific and technical challenge involving the justification of design parameters and the development of a working component for a slot-cutting machine with cycloidal motion. Based on the theoretical and experimental data obtained, the following main conclusions were drawn:

1. Scientific findings: It has been established that the use of the cycloidal motion principle (movement of the cutters along a hypotrochoid) enhances the process of asphalt concrete fragmentation through the vibro-impact action. The theoretically derived dependencies of the cutting force (Equations (1)-

(4)) have been experimentally confirmed with a correlation of 85%, which proves the adequacy of the proposed mathematical model of the working process dynamics.
2. Technical and Economic Efficiency: A comparative analysis of the developed design with existing counterparts (DFM-40, DFM-64) demonstrated a significant advantage of the proposed method. The use of a cycloidal cutting tool reduces the energy consumption of the cutting process by a factor of 1.13 and increases productivity by a factor of 1.18. Under optimal operating conditions (n = 150 rpm), a reduction in cutting force to 30 kN was recorded, compared to 45-50 kN in conventional machines.
3. Practical significance: The results of this study can be applied in the design of new models of the road construction equipment, specifically the ZRM-1 expansion joint cutting machine. The implementation of this technology would improve the quality of the expansion joints cut and reduce operational costs in the construction and repair of highways in Kazakhstan.
4. Areas for future research: Further development of this topic involves studying the wear resistance of cutting elements when working with high-strength cement-concrete pavements, as well as optimizing the mass and dimensional characteristics of the vibration exciter to minimize dynamic loads on the base chassis frame.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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