https://doi.org/10.3311/PPtr.41820

Periodica Polytechnica Transportation Engineering, 54(4), pp. 502–509, 2026

Improving the Efficiency of Processing Complex Automotive Surfaces Using Hand-held Machines with Cycloidal Motion

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Received: 02 August 2025, Accepted: 08 December 2025, Published online: 13 March 2026

Abstract

This paper addresses the pressing practical problem of improving the efficiency of hand-held machines, whose performance in traditional designs has reached its technological limit. It substantiates the high potential of using cycloidal (planetary-rotary) motion for actuators, which opens up new possibilities for processing complex contours, especially when repairing large automotive surfaces. Based on the analysis of satellite curves, the theoretical foundations for the design of such machines have been developed. Hypotrochoidal schemes with an internal envelope are recommended as the simplest and most effective solution, where the scheme with a three-vertex working body ($z=3$) is recognized as optimal. To implement the movement, James' planetary mechanism is proposed, which has high efficiency (0.99) and a rational transmission ratio ($i=3\ldots8$). Mathematical models have been developed that describe the geometry of the working body and the conditions for obtaining straight sections on its trajectory.

Based on these studies, an experimental model of a hand-held polishing and grinding machine has been created. The design with a triangular-shaped working tool allows for high-quality processing of angular and hard-to-reach areas. The introduction of such machines into repair and construction production reduces labor costs by 20…30%, significantly increasing productivity and the quality of surface finishing.

Keywords

working body, cycloidal movement, manual machines, epitrochoid, hypotrochoid

1 Introduction

The development of technology is subject to strict laws: after a period of quantitative growth in parameters, there is a qualitative leap with the emergence of fundamentally new designs (Lukasuk et al., 2018; Volkov et al., 2014; Sherbakov et al., 2021). An analysis of existing hand-held machines shows that they have "exhausted" their reserves for further productivity improvements, which requires the creation of fundamentally new machines, in particular, with planetary-rotary type working bodies. Despite its potential, cycloidal (planetary-rotary) motion has hardly been used in actuators anywhere in the world because of the high manufacturing quality requirements for planetary gears. (Chen et al., 2008; Kamzanov et al., 2023; Sensinger, 2013).

In recent years, planetary gear mechanisms have found increasing practical application not only as mechanisms that transmit motion from the motor to the machine, but also as actuators that use the motion of satellites either directly or in conjunction with a hinge mechanism (Tchufistov et al., 2024a; 2024b; 2025; Wang and Wang, 2009).

The points of the satellites of planetary mechanisms describe the so-called satellite curves; if an executive working body of the machine is connected to the satellite, then, obviously, by designing the mechanism accordingly, it is possible to give the working body of the machine movement along the required trajectory. Several working

Cite this article as: Begimkulova, E., Zhunisbekov, B., Sharipov, Z., Amanova, M., Kyrgyzbay, B., Kozbagarov, R. (2026) "Improving the Efficiency of Processing Complex Automotive Surfaces Using Hand-held Machines with Cycloidal Motion", Periodica Polytechnica Transportation Engineering, 54(4), pp. 502–509. https://doi.org/10.3311/PPtr.41820

bodies can be placed on the satellite: in this case, we will obtain more complex curves consisting of different segments.

As a rule, planetary mechanisms provide the possibility of obtaining large transmission ratios with relatively smaller dimensions compared to other types of gear mechanisms.

This problem is particularly relevant in the field of car repair. The use of traditional round-shaped tools in hand-held machines, rotating around a single axis, does not allow for the processing of corner areas. This work in hard-to-reach places is carried out using low-productivity manual labor. In this regard, there is an urgent need to develop and create machines that would allow finishing work to be carried out efficiently and at minimal cost, both on the main surface and in hard-to-reach places (Bruce and Craig, 1981; Doronkin, 2012; 2018).

The most successful designs for hand-held machines are those with cycloidal motion of the working parts, which utilize the properties of epicycloids and hypocycloids. It is proposed to use this particular feature of movement along involute curves, which will allow for minimal specific energy consumption, significantly reduce the weight and dimensions of the machine, and provide new technological capabilities (Haynes, 1989; Kozbagarov et al., 2021a; 2023).

Based on these principles, an experimental hand-held polishing and grinding machine for large surfaces was developed. If the machine's working tool is made with a triangular profile, then when it moves, all three of its vertices will describe the same line-a hypotrochoid, which practically coincides with the contour of a square, which was the basis for the development of the kinematic scheme for processing in corner areas.

It is precisely this feature of the movement of working bodies (along mutually enveloping curves) that is proposed for use in hand-held machines, which will allow for minimal specific energy consumption during the working process (Ivanov, 2006; Kozbagarov et al., 2021b). In addition, the planetary-rotary motion of the cycloidal working bodies of hand-held machines not only significantly reduces the weight and dimensions of the machine, but also provides new technological capabilities. Another important positive feature of hand-held machines with cycloidal motion of the working body is that they can operate at speeds significantly exceeding those of traditional hand-held machines.

2 Materials and methods

Important areas for accelerating scientific and technological progress include the development, creation, and mastery of fundamentally new techniques and technologies that significantly increase labor productivity. In the creation of such equipment, a special place belongs to its developers, since at the design stage there are ample opportunities to optimize the machine's design and choose the best option from among many technical solutions. Only specialists who are well versed in theory and modern methods of calculation and design of equipment can accomplish this task. Nowadays, full-fledged engineering activities can be ensured on the basis of a broad education that includes not only fundamental physics and mathematics, but also equally thorough methodological training in the field of engineering and technical sciences (Porter, 1985; 1988; 2019; Scharff and Duffy, 1997).

The theory and calculation of hand-held machines with cycloidal motion (planetary-rotary) working bodies, as a specific field of scientific knowledge, covers a wide class of machines and equipment used for the comprehensive mechanization of labor-intensive processes in construction and related sectors of the national economy. These machines are united not only by their field of application, but also by common approaches to calculation and design. The latter allows us to abandon the traditional approach of considering the theory, calculation, and design of each type of machine separately and to focus on the general theoretical provisions, methods, and principles of the issues considered in this work. Thus, the scientific and methodological development of general theoretical foundations for the design of machine working bodies is of great importance, and can even be considered a priority for the design of hand-held machines with cycloidal movement of working bodies.

As a result of the studies conducted (Malhotra and Parameswaran, 1983; Zirtl and Steidle, 2021), it was concluded that the most successful designs for hand-operated machines are those with cycloidal motion of the working parts. These machines use designs with cycloidal shapes of working parts, for which the properties of epicycloids and hypocycloids are used. Usually, such curves are obtained when a point lying inside a circle rolls without slipping on the outer or inner side of a fixed circle (enveloping curves). In manual machines with cycloidal motion of working parts, the formation of an epicycloid is associated with the rolling of the internal gear in a stationary external gear, and the formation of a hypocycloid is associated with the rolling of the external gear on a stationary internal gear. In both cases, the generating point must lie outside the moving circle.

The radii of circles r and R must be integers that differ by one (1/2, 2/3, 3/4, etc.) (Kakinuma et al., 2013; Kamzanov et al., 2023).

By rolling the constructed curve together with a fixed circle around a moving circle, we obtain a family of curves that have outer and inner envelopes.

If the working parts of the machines are designed in such a way so that their cross-sections coincide with the contour of the inner or outer envelope and are arranged side by side on the frame with a gap so that the cross-section of one of them is a mirror image of the cross-section of the other, then when the working parts rotate around two parallel axes, the vertices of each of the cross-sections will describe identical trochoids with straight branches, and the side generatrices of the sections will roll with some slippage along these branches, as if along guides.

The working body of a manual machine with cycloidal motion can be designed based on a trochoid (epicycloid or hypocycloid) or the envelope of a family of curves. Let us consider the theoretical contour of the machine, which is an epicycloid obtained by rolling a large gear with internal teeth over a small fixed gear. The generating point must lie outside the moving circle (Chen et al., 2008; Kamzanov et al., 2023; Sensinger, 2013; Tchufistov et al., 2024a; 2024b; 2025).

The theoretical contour of the machine is a curve formed by the movement of point A, lying on the extension of radius R of a circle with center O_1, which rolls without slipping on a fixed circle of radius r with center O, located inside it (Fig. 1).

Since the relation holds:

$$\frac{r}{R} = \frac{2}{3}, \tag{1}$$

we obtain the following equation $OO_1 = e = R - r = R/3$, where e is the eccentricity.

Due to the absence of sliding (a circle with radius R centered at O_1 rolls without sliding along a fixed circle with radius r centered at O) (Fig. 1 (a)):

$$e\theta = R\psi \ . \tag{2}$$

From here:

$$\psi = \frac{e}{R}\theta = \frac{1}{3}\theta; \ 0 \le \psi \le 2\pi , \tag{3}$$

where:

- ψ – angle of rotation of the generating circle around center O_1;
- θ – angle of rotation of eccentricity OO_1 around center O.

The equation of the epicycloid in vector form will take the form:

$$\vec{\rho} = \begin{Bmatrix} e\cos 3\psi + a\cos\psi , \\ e\sin 3\psi + a\sin\psi \end{Bmatrix} . \tag{4}$$

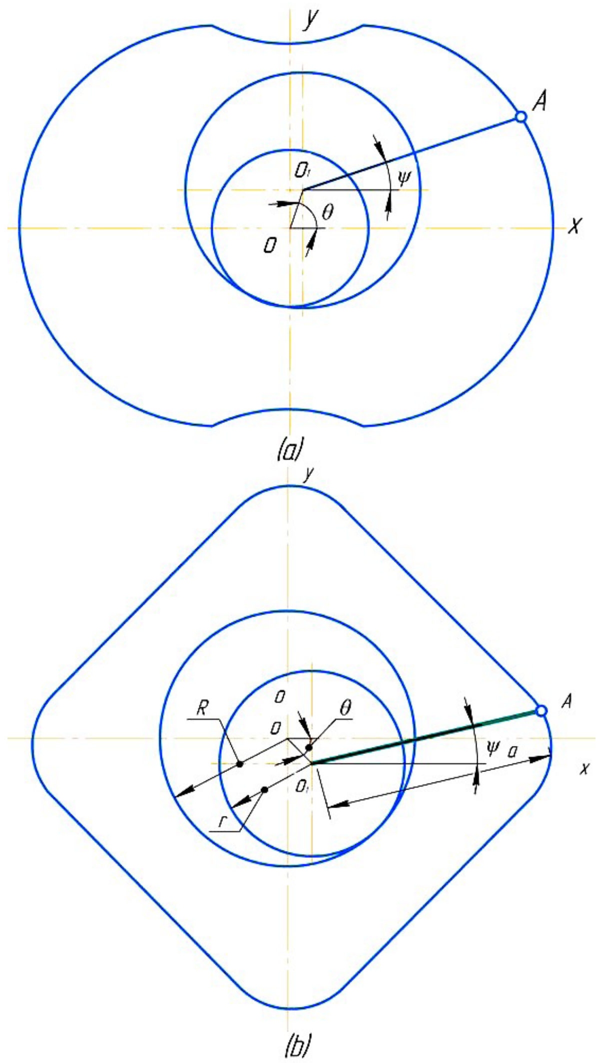

Fig. 1 Calculation diagram: (a) epicycloid; (b) hypocycloid

Moving on to coordinate form, we obtain a system of equations:

$$\left.\begin{aligned} z &= e\cos 3\psi + a\cos\psi \\ y &= e\sin 3\psi + a\sin\psi \end{aligned}\right\} . \tag{5}$$

Let us denote

$$\frac{a}{R} = c, (c > 1) \tag{6}$$

where a is the generating radius.

Then the equation of the epicycloid can be written as:

$$\begin{aligned} x &= R\left(\frac{1}{3}\cos 3\psi + c\cos\psi\right) \\ y &= R\left(\frac{1}{3}\sin 3\psi + c\sin\psi\right) \end{aligned} . \tag{7}$$

Contour equation in polar coordinates (in parametric form):

$$\left.\begin{aligned}\rho &= e\sqrt{1+9c^2+6c\cos 2\psi}\\ \varphi &= arctg\frac{\frac{1}{3}\sin 3\psi + c\sin\psi}{\frac{1}{3}\cos 3\psi + c\cos\psi}\end{aligned}\right\}. \quad (8)$$

Equation (8) shows that the contour consists of two branches, since ρ depends on 2ψ ($0 \le \psi \le 2\pi$).

Area of an epicycloid:

$$\Phi = \frac{1}{2}\int_0^{2\pi}\left(x\frac{dy}{d\psi} - y\frac{dx}{d\psi}\right)d\psi \ . \quad (9)$$

Differentiating Eq. (8) and performing the necessary transformations, after integration we find

$$\Phi = \pi\left(a^2 + 3e^2\right). \quad (10)$$

Let's examine the curvature of the contour, the working body of the machine.

The radius of curvature is given by Eq. (11)

$$p = \frac{\left(x'^2 + y'^2\right)^{\frac{3}{2}}}{\begin{vmatrix} x' & y' \\ x'' & y'' \end{vmatrix}} \ . \quad (11)$$

A regular triangle fits into the contour described by the equation, with its vertices able to slide along the contour. The working body (rotor) is not a straight line, but a curved triangle. The side edge of the rotor can be formed by the inner envelope of a family of epicycloids.

The equation of the family of epicycloids formed during rolling can be written as:

$$\left.\begin{aligned}x &= e\cos 2\lambda + x_1\cos\lambda + y_1\sin\lambda\\ y &= e\sin 2\lambda - x_1\sin\lambda + y_1\cos\lambda\end{aligned}\right\}, \quad (12)$$

where x_1, y_1 is the epitrochoid coordinates in a moving system, determined by Eq. (7).

Let us consider hypotrochoidal diagrams (Fig. 1 (b)):

$$\frac{r}{R} = \frac{z}{z+1}, \quad (13)$$

where z is the number of vertices of the working body.

It is easy to show that, as was done for epicycloids, only those hypotrochoids for which the condition expressed by Eq. (13) is satisfied can serve as contours of the working body of a machine.

Further:

$$e = R - r = \frac{r}{z} \ . \quad (14)$$

Below are formulas that are similar to those given earlier (see Eqs. (3), (5)–(8)):

$$\psi = -\frac{\theta}{z}; 0 \le \psi \le 2\pi \quad (15)$$

The equation of the hypotrochoid in coordinate form:

$$\left.\begin{aligned}x &= e\cos z\ \psi + a\cos\psi\\ y &= -e\sin z\ \psi + a\sin\psi\end{aligned}\right\}. \quad (16)$$

Let us denote:

$$\frac{a}{r} = c, \ (c > 1), \quad (17)$$

then the equation of the hypotrochoid can be written as:

$$\left.\begin{aligned}x &= R\left(\frac{1}{z}\cos z\ \psi + c\cos\psi\right)\\ y &= R\left(-\frac{1}{z}\sin z\ \psi + c\sin\psi\right)\end{aligned}\right\} \quad (18)$$

Contour equation in polar coordinates (in parametric form):

$$\left.\begin{aligned}\rho &= e\sqrt{1+z^2c^2+2zc\cos(z+1)\psi}\\ \varphi &= arctg\frac{-\frac{1}{z}\sin z\ \psi + c\sin\psi}{\frac{1}{z}\cos z\ \psi + c\cos\psi}\end{aligned}\right\}. \quad (19)$$

Since ρ depends on $(z + 1)\ \psi$ ($0 \le \psi \le 2\pi$), the contour of the working body consists of z + 1 branches.

By analogy with Eq. (8), we have the area of the hypotrochoid:

$$\Phi = \pi\left(a^2 - ze^2\right). \quad (20)$$

Contour curvature radius:

$$p = -\frac{r\left[1+c^2-2c\cos(z+1)\psi\right]^{\frac{3}{2}}}{-z+c^2+(z-1)c\cos(z+1)\psi} \ . \quad (21)$$

A significant advantage of epicycloids and hypocycloids over other curves is that their formation is associated only with rotational movements, as a result of which the kinematic scheme of cycloidal machines is extremely simple.

In cycloidal machines, either the rotor or the housing, or both the rotor and the housing, can rotate. In the first two cases, the rotor or housing performs planetary motion-they rotate together with the movable gear around its center, which in turn rotates around the center of the fixed gear. In the latter case, we obtain a birotational machine in which the rotor and housing rotate around fixed axes passing through the centers of the gears, with speeds corresponding to the gear ratio. The only advantage of this design is the absence of unbalanced inertial forces. However, the birotative scheme and the scheme with a rotating housing are very inconvenient (especially for construction and road machines) and require the solution of a number of complex design problems. The rotating rotor scheme is much simpler, despite the fact that the planetary motion of the rotor generates a centrifugal inertial force, which must be balanced.

Thus, among the various cycloidal machine designs, the simplest is the design with a fixed housing, rotating rotor, and internal envelope. Therefore, we recommend hypotrochoid machine designs with an internal envelope.

The theoretical contour of the working body of a machine with cycloidal motion is a hypotrochoid obtained by rolling the external gear on a fixed internal gear. The generating point must lie outside the moving circle. The cross-section of the working body of a construction machine is usually a flat polygonal figure, the points of which, when rotating around two parallel axes, describe curved lines – hypotrochoids (hypocycloids).

Our research has shown that James' planetary mechanism is the most promising, and we have applied it in the working parts of construction and road-building machines as a power reducer. This mechanism, with drive wheel 1 and driven wheel *N*, has a sufficiently high efficiency coefficient (Fig. 2).

It differs favorably from other planetary mechanisms in its compactness and relatively small dimensions, since the entire mechanism is mounted inside the ring gear 3.

It should be noted that planetary mechanisms almost never use a single 2 satellite. Usually, there are several satellites, from 2 to 20 (usually 3 or 4), which engage with the same wheels. This is done to balance the forces of inertia and relieve the load on the mechanism's gear wheels. When determining the degree of mobility of a gear mechanism, all added satellites (more than one) are passive links and are not taken into account in the calculations. From the many designs of planetary mechanisms for the working bodies of construction and road machines, those with a higher transmission ratio and efficiency coefficient should be used. For James' planetary mechanism, the rational transmission ratio is $i = 3…8$, and the efficiency coefficient is 0.99.

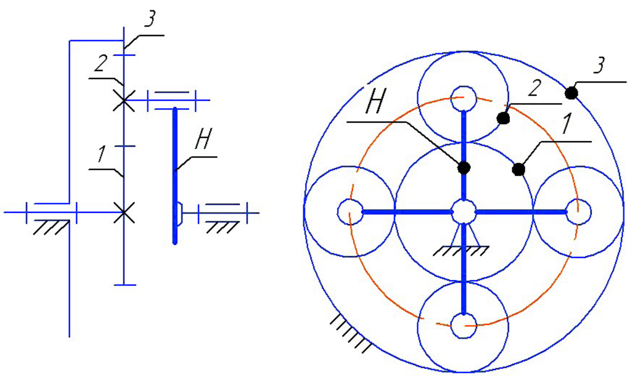

Fig. 2 James's mechanism

3 Results and discussions

Based on theoretical research, a hand-held polishing and grinding machine for large surfaces was developed and created. These machines use grinding wheels that rotate around a horizontal axis or discs with a flat working surface that rotate around a vertical axis as working tools.

The use of traditional round tools rotating around a single axis in hand-held machines does not allow for the processing of corner areas directly. Processing in such hard-to-reach areas is usually carried out using hand tools and low-productivity manual labor.

In this regard, there is an urgent need to develop and create machines that would allow finishing work to be carried out efficiently and with minimal manual labor, both on the main surface and in hard-to-reach areas.

The main technical requirements for the machine being developed were as follows:

1. The machine must be multi-purpose and, if necessary, by installing the appropriate tool, ensure high-quality grinding of the surface of coatings, both on the main area and in hard-to-reach places;
2. The machine should be relatively small in size, dimensions, and weight;
3. The machine must be powered from a single-phase AC mains supply with an industrial frequency of 50 Hz.

In the basic version, the machine design consists of a planetary mechanism 3 with a working tool 4, an electric motor 2, and a control handle 1 (Fig. 3 (a) and (b)). If the working tool of the machine for machining various surfaces is made with a triangular profile, then when moving, all three of its vertices will describe the same line-a hypotrochoid, which practically coincides with the contour of a square, which was the basis for the development of the kinematic scheme of the machine for machining various surfaces in angular areas.

The shape of the hypotrochoid and the number of its branches depend on the value of the generating radius a (a is the distance from the center of the generating circle to the generating point) and the values of the radii of the guide circle *R* and the generating circle *r*. If the radii are integers that differ by one, for example, $R / r = z + 1/3 = 3/2, 4/5, 5/4$ and so on, then each of the corresponding hypotrochoids forms a flat figure with $z + 1$ congruent branches and the same number of vertices (triangle, quadrangle, pentagon). Depending on the value of the shape parameter $c = a / r$, the branches of the hypotrochoid can be concave, convex, or have straight sections.

From the point of view of their use in kinematic diagrams of machines for processing various surfaces in angular

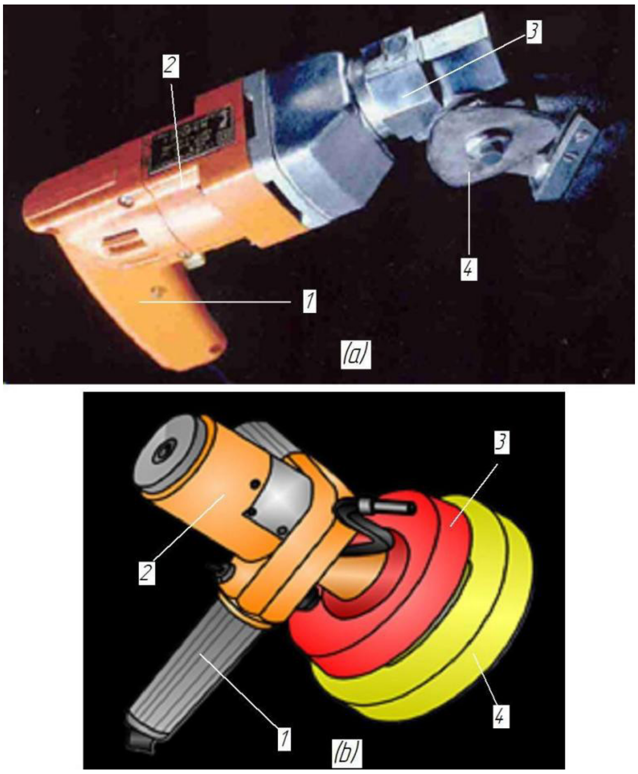

Fig. 3 Experimental hand-held machine: (a) for cutting and grinding; (b) for polishing and grinding

sections, there are variants of ratios $R / r = z+1/ z = 4/3$ and $c = a / r = 2.5$.

The kinematic diagram of the machine (Fig. 4) is implemented using a planetary mechanism. The planetary mechanism is designed as a cylindrical head and contains a central gear wheel 1 with internal teeth that mesh with the teeth of gear 3. The ratio of the pitch circle radius of the pinion is taken to be 4/3. The transmission ratio of the planetary mechanism at the drive shaft is 3. The shaft 2 is mounted in the planetary mechanism housing on bearings 7. The electric motor shaft 4 is rigidly connected to the shaft. Gear 3 is rigidly connected to shaft 5, which is mounted on bearings 6 in the cylindrical bore of drive 2. The bore is located eccentrically relative to the axis of rotation of the drive. A faceplate 8 with a working tool 9 is fixed at the end of shaft 5.

If the working tool of the machine is made with a triangular profile, then when moving, all three of its vertices will describe the same line-a hypotrochoid, which practically coincides with the contour of a square. This allows the tool, inscribed in this contour, to move inside it and effectively process the coating in the corner areas.

The tool profile has the shape of a regular triangle with convex sides (Fig. 5). Its center coincides with the axis of rotation of the gear. The ratio of the distance from the center of the tool to any of its vertices to the radius of the gear is 2.5.

The working tool differs from known tools in that the contour of its working surface edge coincides with the contour of the inner envelope of a trochoid family. The working edge of the tool can be made in the form of a regular triangle, the sides of which are formed by arcs of a circle with centers located on opposite sides to the vertices of the triangle. Other arrangements of the cutting edges are also possible; in particular, they can be arranged radially or at an angle to the radius.

The triangular grinding tool (Fig. 4) is made of abrasive material. It uses crushed glass as an abrasive and Bakelite resin as a binder. A characteristic feature of this abrasive material is that it does not become clogged with filings during grinding, but, as it wears down, layer by layer, it is renewed, that is, it sharpens itself.

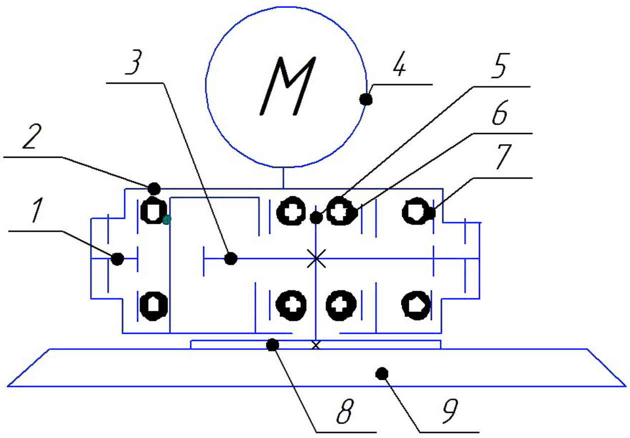

Fig. 4 Kinematic diagram of the experimental hand-held machine

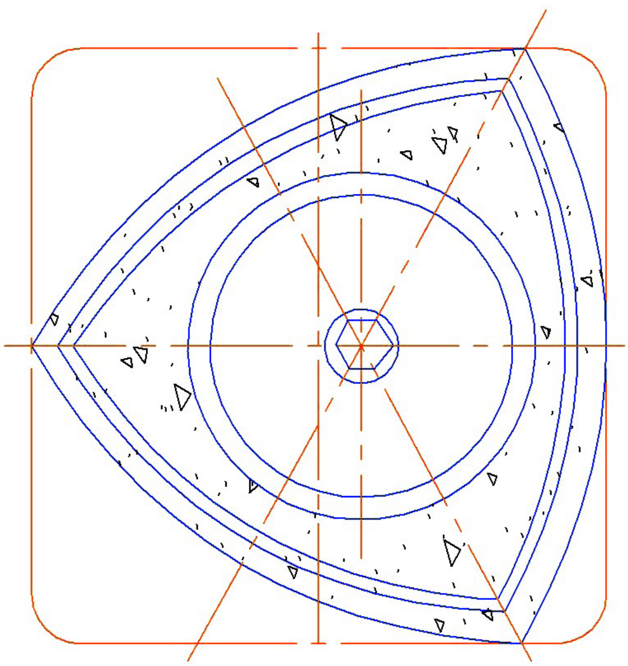

Fig. 5 Work tool profile

The tool is located in the console part of the machine, which is 8 mm high and has a reach of 22 mm, allowing it to process hard-to-reach areas. The machine operates as follows: when the electric motors are switched on, the rotation from its shaft is transmitted to the drive 2 of the planetary mechanism. As a result, gear 3, rotating around two parallel axes, performs a planetary motion. Together with the gear, the working tool 9, which is connected to it, performs a planetary plane-parallel movement. With the above-mentioned kinematic features and geometric parameters of the planetary gear and the tool, each of its vertices describes the same line-a hypotrochoid, which practically coincides with the contour of a square. The tool inscribed in this contour moves inside it, making it possible to process the coating in the corner areas.

Improving the technical level of production is one of the most important measures aimed at reducing the cost of production. Improving technical equipment, introducing new machines, mechanization, and automation of main and auxiliary production reduce the cost of work.

In this work, the fundamentally new design of the working body significantly increases productivity and reduces metal consumption.

When grinding equipment, numerous abrasive grains, acting as micro-cutters, penetrate the surface of the coating, forming micro-scratches that intersect each other multiple times at different angles, resulting in the removal of a significant layer, improved processing quality (surface cleanliness), and increased grinding process productivity.

The machine is easy to operate and convenient for processing surfaces in corners and hard-to-reach areas.

Based on the developed design, it is possible to create highly efficient machines for mechanical processing of various surfaces, both on the main area and in hard-to-reach places. The economic effect of introducing such a machine into repair and construction production is due to a 20...30% reduction in labor costs and an increase in productivity and surface processing quality.

4 Conclusions

Research conducted on the development of machines with cycloidal motion of working parts has yielded scientifically sound results, the application of which provides a solution to a major practical problem of improving the efficiency of hand-held machines for the country's construction industry. The following main conclusions were drawn from the work:

- Based on an analysis of research in the field of creating new working equipment for hand-held machines with cycloidal motion, the parameters and effectiveness of using cycloidal working motions, in which the trajectories of mutually enveloping satellite curves are used to perform technological operations, are justified. The use of mutually enveloping satellite curves in the working equipment of hand-held machines has made it possible to achieve minimum specific energy consumption of the working process and expand the technological capabilities of the machines;
- Mathematical models of theoretical cycloidal working parts of machines have been developed. These models are based on optimal geometry, ensuring minimum specific energy consumption, and have made it possible to apply modern automatic design systems in the design of cycloidal working equipment.

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