Design and Technological Support for the Manufacture of Cardioid Cams of Paper Drilling Machines

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***Abstract*— Despite the rapid development of information technology and various electronic media, paper remains the main material in the printing industry. Drilling machines plays an important role in such industry, and cardioid cams are significant parts of them. The mechanism for cutting of cardioid cam is studied in paper. Its kinematic is calculated, the equation of trajectory of cutting tool centre is obtained. The problem of calculation of cutting tool edge is considered. The optimization task for creation a mechanism, which produce the most precise trajectory of cutting edge is set. The solution od such a task is offered and optimization criteria are offered.**

***Index Terms*—paper-drilling, cardioid, Limaçon, cam, plasma cutting, machine tool**

I. Introduction

Despite the rapid development of information technology and various electronic media, paper remains the main material in the printing industry. It has existed for more than 2000 years, and people still do not refuse books, magazines, newspapers, calendars and many other "paper" publications.

In the modern world, mechanization and automation is implemented in every production enterprise. So, for use in printing and paperwork, paper-drilling machines were created. The scope of this equipment is the most diverse. This is the archiving of documents for various purposes, the extinguishing of securities, the creation of catalogs, loose-leaf calendars, the manufacture of blocks for organizers and tags for goods. Perhaps drilling paper, cardboard, textiles, leather and artificial materials. Paper-boring machines have become indispensable “employees” in banks, archives, libraries and large organizations with a large workflow.

The main purpose of the device is punching (drilling) of round holes of various diameters in bundles of paper and cardboard for various needs: for a folder, for flip calendars, organizers, for binding with metal springs.

Drills for paper differ among themselves desktop or floor execution, the number of drill heads, the degree of automation, the diameter of the drills used and so on. But, like any mechanical system, all paper-drilling machines consist of many flat and spatial mechanisms. In this variety, cam mechanisms occupy an important place. Their main advantage is the ability to implement complex transfer functions with just two links: a cam and a pusher, forming a higher kinematic pair.

The Dürselen PB.04N Paper Drilling Machine (High Performance Paper Drill Dürselen PB.04 N) is a professional high-performance drill suitable for all standard perforations, complex annular perforations and for creating rows of holes for a wire comb.

This machine includes all the functions for drilling holes of any diameter and processing complex materials such as coated paper or plastic film.

Even in continuous operation, the machine is completely maintenance free.

a

b

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Figure 1. Drilling machine Dürselen PB.04N (a), and its cardioid cam (b,c)

The important part of such a machine is carioid cam. In the case of a single production for the manufacture of such cams it is rational to use CNC machines, however, in mass production, if there is no need for readjustment of equipment, cardioid cams can be rationally manufactured using mechanical forming equipment [1].

II. Qualitative Indicators

To develop such an equipment the following qualitative indicators should be considered:

- Accuracy
- Performance
- Reliability and wear resistance

Accuracy is necessary in order to withstand the same geometric dimensions in the manufacture of the same parts with a minimum path error. Errors in geometric parameters are not only inevitable, but also permissible to the extent that the part still meets the requirements for proper assembly, operation of the machine and provides quality indicators. It is impossible to demand obtaining an absolutely accurate (ideal) value of a parameter, that is, a zero error, since this requirement is not feasible in real production and measurement conditions [2 – 8].

This mechanism moves along the cardioid. We set the width of the deviation from the trajectory depending on the overall size of the part manufactured using machine tool equipment, as well as on the basis of the features of cutting. Since plasma cutting, the accuracy is quite high, deviations appear only from the thickness of the plasma torch jet. Torch nozzle - 3 mm. We take the possible deviation equal to half the nozzle of the torch. Then the bandwidth of possible deviations will be equal to 1.5 mm.

To implement the cutting process, the working bodies of the machine are informed of the necessary movements. At the same time, a metal layer is cut off from the workpiece and the state of the treated surface changes. These include the main movement and the feed movement.

The implementation of the main and auxiliary movements requires a quantitative assessment. The main movement has the highest speed and, therefore, determines the direction and speed of deformation of the sheared metal layer, the direction of the chip flow and its shape.

Therefore, the speed of the main movement is the cutting speed.

Due to the small thickness of the manufactured part, the requirement for a maximally flat cam surface and its complex shape, it is advisable to use plasma technology for cutting. Plasma cutter provides simplicity and accuracy of cutting, eliminates additional loads on the mechanism, which are delivered, for example, milling cutters, cutters, drills and countersink. The obvious advantages over other types of cutting along with laser technology are the ability to cut complex contours, the absence of material deformation, the absence of subsequent processing, minimal costs, and production wastes are minimized. This is achieved due to the lack of contact between the metal and the cutting device. The slice that is formed during the cutting process has high purity and surface quality. In addition, a plasma cutter requires less power than a laser. The cutting technique is very simple and consists in uniformly moving the cutting head along the cutting line as the entire thickness of the workpiece is cut. In this case, the perpendicularity of the axis of the head of the surface of the cut object should be maintained. At the starting point of the cut, the cutter must be held up until the entire thickness of the material is cut completely.

Cutting metal using a plasma jet allows complex curly notching. The technology involves various modes of plasma cutting of metal, which allows you to quickly adjust the equipment to work not only with a certain kind of alloy, but also with workpieces of a certain thickness. In the reference book, it was revealed that for cutting GOST 12X18H10T steel, a torch nozzle with a diameter of 3 mm should be selected. The required amount of air with this cutting is 40-60 l / min. Also, when considering plasma cutting modes, it was revealed that for cutting steel of a given thickness, it is necessary to provide a current strength of the source of 250-300 A. Among the possible cutting modes, we choose one that satisfies the optimal and convenient cutting speed. So, a speed of 2.1 m / min was chosen. To ensure a given cutting speed, you need to apply a voltage of 160-180 V. The average width of the cut in this case will be 4 mm. For the designed cam, a type of steel was chosen - 12X18H10T based on the need to ensure high hardness of the part and reliability, which is especially important when working in conditions of wear in machine equipment.

Thus, based on the selected cutting speed, the specified material and the thickness of the part, based on the table of plasma cutting modes, other parameters were established, such as voltage, current, cutting width, nozzle diameter and air flow. The cutting speed was set based on the calculation of the time to manufacture one part.

Reliability is a manifestation of all material properties during operation.

The criterion for the reliability of the mechanism will be considered the allowable wear of the parts of the mechanism for a certain number of work cycles. As a material for the manufacture of parts, we take structural steel 45.

Steel 45 is a structural carbon alloy steel of pearlite class. Parts are made of steel 45, which are subject to the requirements of increased hardness, wear resistance, strength and work at low impact loads.

We assume that the mechanism will retain its reliability after 10,000 uses [9].

III. Optimization of the Mechanism from the Point of View of the Described Trajectory

Terminology:

- Ideal path - the target path along which the torch should move to draw a given cam profile.
- Real trajectory - the trajectory along which the cutter is able to move when using the original mechanism.
- Error width - the maximum permissible deviation of the real trajectory from the ideal, when comparing them in some node.
- Node - discrete value (point) on an ideal trajectory during its discretization.

Perfect trajectory:

It is known that the profile of the cut cam is described by the cardioid equation.

$$\begin{cases} x(t) = 2a\cos(t) + a\cos(2t) + a; \\ y(t) = 2a\sin(t) + a\sin(2t); \end{cases} \quad (1)$$

On the other hand, when cutting the cam, the cut width must also be taken into account. It is also known that for a parametrically defined curve, a parallel curve passing from it at a distance h is determined by the equations:

$$\begin{cases} X(t) = x(t) + \frac{h \cdot y'}{\sqrt{(x')^2 + (y')^2}}; \\ Y(t) = y(t) - \frac{h \cdot x'}{\sqrt{(x')^2 + (y')^2}}; \end{cases} \quad (2)$$

Subsequently, by substitution and transformation, we obtained the parametric equation of an ideal trajectory:

$$\begin{cases} X_t(t) = a \cdot (2\cos(t) + \cos(2t) + 1) + h \cdot \cos\left(\frac{3t}{2}\right); \\ Y_t(t) = a \cdot \left(2\sin(t) + \sin(2t)\right) + h \cdot \sin\left(\frac{3t}{2}\right). \end{cases} \quad (3)$$

Real trajectory:

To determine the real trajectory, it is necessary to derive its equation and express it through the geometric parameters of the mechanism. For clarity, consider the following sketch.

As geometric parameters we will use the following quantities (Fig. 2):

- H is the distance between the rotational kinematic pairs;
- L is the distance from the point of rigid fastening of the wings to the cutting device.

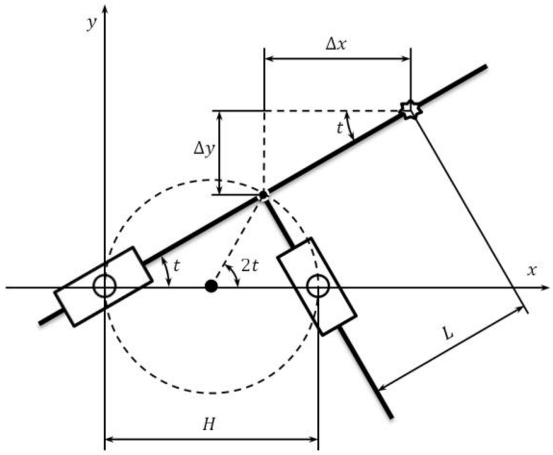

Figure 2. Plot for calculation of mechanisms geometry

It can be easily revealed that in this mechanism the link point of the wings on the connecting rod moves along the trajectory described by the equation of the circle.

$$\begin{cases} x(\varphi) = x_0 + R\cos(\varphi); \\ y(\varphi) = y_0 + R\sin(\varphi); \end{cases} \quad (4)$$

Parametric equation of a circle in which x_0 and y_0 are the coordinates of the center of the circle.

In our case: $x_0 = \frac{H}{2}$, $y_0 = 0$, $R = \frac{H}{2}$, $\varphi = 2t$:

$$\begin{cases} x(t) = \frac{H}{2} + \frac{H}{2} \cdot \cos(2t); \\ y(t) = \frac{H}{2} \cdot \sin(2t); \end{cases} \quad (5)$$

The resulting equation describes the position of the link point of the wings. Now you need to find the offset of the cutting device from this point. It is characterized by values Δx and Δy:

$$\begin{cases} \Delta x(t) = L \cdot \cos(t); \\ \Delta y(t) = L \cdot \sin(t); \end{cases} \quad (6)$$

Thus, the position of the cutting device can be determined by the following parametric equation:

$$\begin{cases} X_r(t) = L \cdot \cos(t) + \frac{H}{2} \cdot \cos(2t) + \frac{H}{2}; \\ Y_r(t) = L \cdot \sin(t) + \frac{H}{2} \cdot \sin(2t). \end{cases} \quad (7)$$

This equation is the Pascal snail parametric equation.

It is necessary to determine such parameters H and L so that the real and ideal trajectories coincide with a given degree of accuracy, provided that it is possible to manufacture elements of the mechanism with some accuracy.

Preparatory stage:

In order to be able to compare the ideal trajectory with the real one, it is necessary to somehow relate them to each other. To do this, it is enough to determine for them a certain common point, which will always have the same coordinates, and it can always be determined by the equation of the trajectory by a certain value of the parameter t. An example of such a point may be the origin. Now the question arises of which point for each of the trajectories must be associated with the origin. We know that both equations are defined for $Y(t) = 0$. This means that they have common points with the axis Ox. Choosing any of them, we will simplify our task by the fact that to combine the graphs, it will be enough to simply shift them along the Ox axis. The simplest and most obvious is the choice of points on both graphs, which are associated with a single parameter value t = 0.

Define the coordinates of these points along the abscises:

$$X_t(0) = 4a + h;$$
$$X_r(0) = L + H. \tag{8}$$

Now, in order to relate the graphs of these functions at the origin, it is necessary to rewrite their equations taking into account the displacement:

$$\begin{cases} X_t(t) = a \cdot (2cos(t) + cos(2t) + 1) + h \cdot cos\left(\frac{3t}{2}\right) - (4a + h); \\ Y_t(t) = a \cdot (2sin(t) + sin(2t)) + h \cdot sin\left(\frac{3t}{2}\right) \end{cases} \tag{9}$$

$$\begin{cases} X_r(t) = L \cdot cos(t) + \frac{H}{2} \cdot cos(2t) + \frac{H}{2} - (L + H); \\ Y_r(t) = L \cdot sin(t) + \frac{H}{2} \cdot sin(2t). \end{cases} \tag{10}$$

IV. Mechanism Optimization Algorithm

As mentioned earlier, it is necessary to determine such geometric parameters of the mechanism so that the ideal path coincides with the real one at a given accuracy.

Let us take the following position: Two curves are equal with some degree of accuracy if, when discretizing one of these curves, for each of its discrete values (nodes), the displacement of a point on the other curve from it along the normal to the discretized curve does not exceed some allowable error value.

Among the two given curves, we will discretize the curve characterizing the ideal trajectory based on the fact that it has no dynamic parameters (not counting the variable t). The curve characterizing the real trajectory will change during the work by the dynamic parameters H and L, in order to find the optimal trajectory comparable with the ideal one. The value of the allowed error will be called the error width, and denoted by Δd. Visually a similar model can be represented as follows:

To control the occurrence of a real path in the width of the permissible error of an ideal path in a certain node, it is logical to decide to find the distance between this node and the intersection point of the normal drawn through the node and the real path. And then compare it with the value of the width of the error. But when considering such a problem, it becomes necessary for each node to find the intersection point of the normal and the curve (Pascal's snail). And in the case of our curve, the number of such points may be greater, depending on the form of the equation. From this follows the problem of finding the roots of an equation, which can be obtained from the original equations by substituting one into the other. The solution of problems of this kind is carried out by iterative methods or mathematical algorithms and transformations. But when considering two approaches, it turned out that their application in our case is not rational. Iterative methods will add significant computational loads to the optimization algorithm, since it becomes necessary to apply them to each node, the number of which is quite large. As for mathematical algorithms and transformations, the most promising was the consideration of the original equations in a general way. But when one of them is substituted into another, a polynomial of degree 4 arises, and finding the roots of the resulting equation is a rather laborious and difficult task [10 – 14].

In light of the above problems, it is not advisable to use a similar criterion for comparing curves. A less stringent comparison criterion can be set, but it also has its own negative features. Another option involves checking the intersection of the real path with the width of the error. Such a check can be carried out if the position of the extreme (from the node) points on the segment of the error width relative to the real trajectory is determined. Since we know that this trajectory is described by the Pascal snail equation, which generally characterizes a closed curve, we can check whether each of the points on the segment belongs to the interior of the closed curve or not (see Fig. 3).

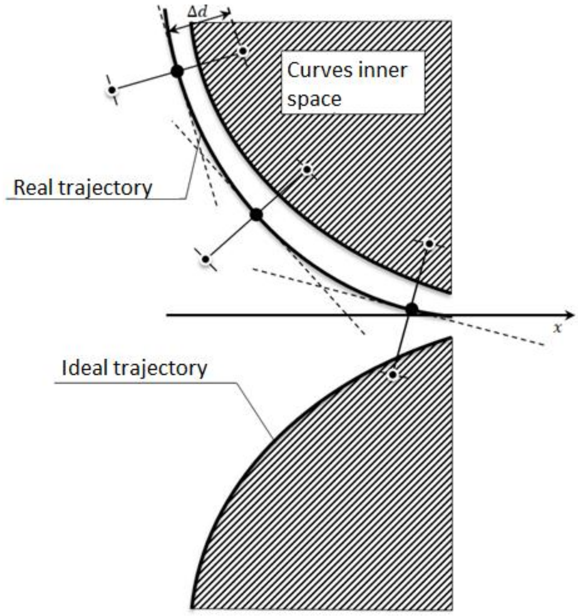

Figure 3. On determination of optimization criteria

If one belongs and the other does not, then this means that the curve intersects a segment of the error width. Otherwise, it does not cross it or crosses an even number of times. Actually multiple intersection is one of the disadvantages of using such a comparison criterion. Another disadvantage is manifested in cases where the extreme point on the segment of the error width has a negative coordinate along the ordinate axis. Pascal's snail equation in general describes it in its entirety, but when comparing it, we take into account only half of it. Due to the specifics of the mechanism, our equation is considered for t∈ (0, π), that is, only in the upper half-plane. The essence of the problem is that, for example, for some node, a curve defined by a general equation can simultaneously intersect a segment of the error width, both in the upper half-plane and in the lower.

To solve such problems, we will trim that half of the segment of the error width that turned out to be in the lower half-plane, that is, the extreme point that appears in the lower half-plane will become the intersection point of the segment with the abscissa axis.

Returning to the problem of multiple intersection, a similar drawback, after making the last adjustments, appears to be insignificant (at least in our case). Under such conditions, it will now manifest itself only if we choose the magnitude of the error width large enough, even larger, for example, of parameter a from the ideal trajectory equation. For reasons of reason, we do not consider such large values, which means that we can completely neglect this drawback.

Now that we have defined the comparison criterion, we can proceed directly to the algorithmization. The following parameters will be input to the algorithm:

number of nodes (COUNT);
precision manufacturing of mechanism elements (STEP);
error width value (ERRSHIFT);
the upper limit of the parameter H (HIGH_H);
lower limit of parameter H (LOW_H);
upper limit of parameter L (HIGH_L);
lower limit of parameter L (LOW_L).

All other model parameters are already predetermined:
a = 25 mm;
h = 2 mm;

The ideal trajectory will be discretized with respect to the parameter t under the following conditions:
tSTART = 0 rad;
tFINISH = 2.7329 rad;
tSTEP = $(t_{FINISH} - t_{START})/COUNT$ rad.

The value tFINISH characterizes the value of the parameter t at which the ideal trajectory crosses the abscissa axis. This is due to the fact that the equation of this curve in the parametric form at t ∈ $(0,\pi)$, in contrast to the Pascal snail equation, is defined in both half-planes. But we should not perform the verification of comparison of curves in the lower half-plane, as was already mentioned above. The value of tFINISH was determined iteratively and its accuracy (the number of decimal places) ensued from such an iterative step at which the error in determining the root along the ordinate axis did not exceed 0.001 mm.

With an accuracy of manufacturing elements of the mechanism of 0.01 mm and an accuracy of reproduction of the curve of 0.075 mm, the following mechanism parameters were obtained:
H = 59.45 mm;
L = 47.52 mm.

Returning to the synthesis of the main mechanism, these are so far the only parameters of the mechanism that we can determine at this stage. The rest will be determined in further calculations.

V. Working Mechanism Construction and Calculation

To design the links of such a mechanical tool, the forces emerge in working process should be considered.

The force calculation scheme for mechanism is given on Fig. 4.

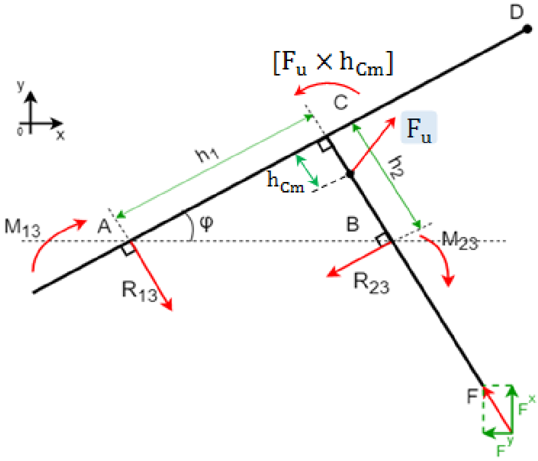

Figure 4. Plot for calculation loads

The loads may be determined by mean of linear system solution:

$$H := AB \qquad h_1(\varphi) := H \cdot \cos(\varphi) \qquad F := 100$$
$$h_2(\varphi) := H \cdot \sin(\varphi) \qquad F_u(\varphi) := m \cdot a_{Cm}(\varphi)$$

$$A(\varphi) := \begin{bmatrix} -1 & 0 & -\sin(\varphi) & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & \cos(\varphi) & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 & \cos(\varphi) & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & \sin(\varphi) & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & \sin(\varphi) & 0 & -\cos(\varphi) & 0 & 0 & 0 & 0 \\ 0 & 0 & -\cos(\varphi) & 0 & -\sin(\varphi) & 0 & 0 & 0 & 0 \\ 0 & 0 & h_1(\varphi) & -1 & -h_1(\varphi) & 1 & 0 & 0 & 0 \end{bmatrix}$$

$$b(\varphi) := \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ F \cdot \sin(\varphi) - F_u(\varphi) \cdot \sin(\theta_2(\varphi)) \\ -F \cdot \cos(\varphi) - F_u(\varphi) \cdot \cos(\theta_2(\varphi)) \\ -F_u(\varphi) \cdot h_{Cm} \cdot \sin(\theta_1(\varphi)) \end{bmatrix}$$

Using this loads, the stresses in construction were calculated using ANSYS [15 – 17] (see Fig. 5).

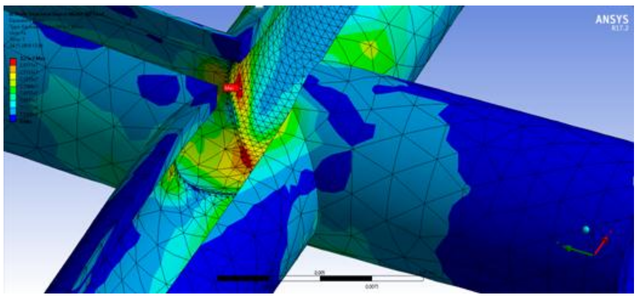

Figure 5. Finite element model of mechanism link and stresses calculation

By means of series of iteration, the optimal geometry for such a mechanism being obtained [18]. The optimal mechanism construction is shown on Fig. 6.

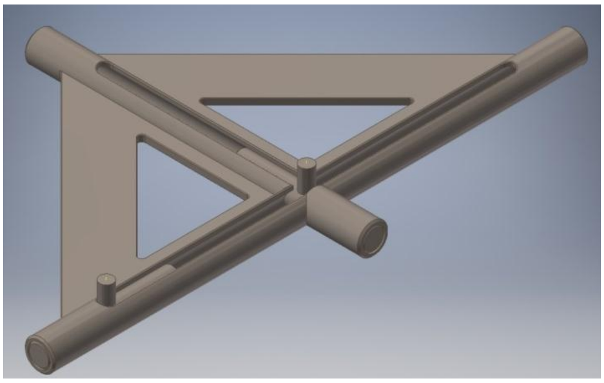

Figure 6. Optimal construction of tool for cardioid cam cutting

VI. Discussion

The problem shown in the article may be seen as not so serious because of wide usage of CNC-machines for cam production. On the one hand it is fully justified because of the variety of its forms. On the other hand it is know that due to the dynamics of milling machine some defects may occur at the points of cam profile intersection with coordinate axis. Due to the coincidence of this points with special points on movement law of cam mechanism, it is an important problem.

Moreover in case of mass production it is much more efficient to use the special equipment instead of programmable machines as it increases the production efficiency and reduce the requirements for operators qualification.

The proposed mechanism of specialized machine tool allows plasma cutting of cardioid cam in polar coordinates with increased precision and automation, which makes it usable in drilling machines tools production.

VII. Conclusion

The conducted research helps to find possible ways to organize effective ways for production of cardioid cams for paper-drilling machines.

The mechanism for cardioid cam production construction is calculated. For the purpose of precision of produced cam the links length is calculated with optimization algorithm.

For the optimization of trajectory of plasma ray a range of algorithms is concerned. As the real trajectory is Limaçon, it is possible to optimize it as equidistant with its equation. On the other hand, such a ways are highly difficult in calculations, that's why a new stringent comparison criterion is proposed. Some problems of such a criteria is analyzed, and their insignificance in this case is shown.

After the optimization of construction the loads and forces are calculated and the constructions of links are finalized.

As a result of work the following improvement may be made:

- Improvement of optimization function for other types of curves and cam profiles;
- Development of readjustable machine tool for a range of shapes and sizes.

Conflict of Interest

The authors declare no conflict of interest.

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