The synthesis of motion laws for cam mechanisms with additional movement of the follower

Yu I Podgornyj1, 2, V Yu Skeéba1, A V Kirillov1, 3, N V Martyushev4, M A Borisov5

1 Novosibirsk State Technical University, 20, Prospekt K. Marksa, Novosibirsk, 630073, Russia
2 Novosibirsk Technological Institute (branch) Russian State University named after A.N. Kosygin (Technology. Design. Art), 35, Krasny Prospect (5 Potaninskaya St.), Novosibirsk, 630099, Russia
3 Novosibirsk State Pedagogical University, 28, Viluiskaya St. Novosibirsk, 630126, Russia
4 Tomsk Polytechnic University, Lenin ave., 50, Tomsk, 634050, Russia
5 Ulianov Chuvash State University, 15, Moscow ave., Cheboksary, 128010, Russia

E-mail: skeéba_vadim@mail.ru

Abstract. The research discusses the design of cam mechanisms for special purposes. The analysis of the scientific literature on this issue indicates that at present the synthesis of the cam mechanisms motion laws is carried out mainly using a standard set of acceleration curves or displacements. In some cases, the designer needs to synthesize an acceleration law which should be task-specific and provide for a certain production step. Additional areas on the cam profile which perform specified motions of the follower are very important for the synthesis of such mechanisms. There may be several areas of this type. The relevance of the study is due to the fact that the mechanisms that work using a time-compressed cyclic diagram cannot be modernized on the basis of the existing methods for the synthesis of cam mechanisms; therefore, it is not possible to enhance the performance of such mechanisms without a significant change in the laws of motion.

1. Introduction
Currently, there is a large variety of cam mechanisms operating on cyclic diagrams in the practice of automatic machines use. The practice of camshaft automatic machines use indicates that it is impossible to improve performance without a significant change in the motion laws of individual mechanisms. First of all, it is necessary to upgrade those mechanisms that operate on a cyclic diagram with fixed time. A strictly specific time is allotted for their work, which must be taken into account in the dynamic synthesis of the motion laws for such mechanisms. In the scientific literature, considerable attention is paid to the synthesis of mechanisms that have cams in the drive; one can also find the methods of the cam mechanisms laws synthesis for various forms of acceleration. In certain cases, a designer needs to synthesize an acceleration law with a view of a specific task which should provide for a certain production step. Therefore, the aim of the work is to develop a method for synthesizing the cam
mechanism motion law which takes into account the momentum impacting the follower in the initial period of its movement.

Considering this goal, the work poses the following tasks:

- to synthesize a specific motion law for the cam mechanism follower with an additional section of the cam profile which provides for reporting an additional motion to the follower in order to reduce the momentum impacting it;
- to determine the numerical values of the accelerations, speeds and displacements of the follower;
- to carry out the necessary calculations and build a cam profile for implementing the proposed law.

The motion laws of the cam mechanisms are determined by the phase angle of the cam rotation, the magnitude of the rocker, and the necessary mechanism duration, expressed mainly by the contact stresses in the cam-roller pair, or the wear resistance of the pair. Oscillatory phenomena are of special significance for dynamically loaded mechanisms; the impact of these phenomena will also determine the initial momentum when the mechanism moves. The greatest loads should be expected when the frequencies of the system free oscillations coincide with the frequencies of forced oscillations.

The cam mechanisms synthesis comprises several stages: 1) defining the motion law of the rocker for the follower swinging motion or the travel of the follower for progressive motion; 2) defining the mechanism design or kinematic parameters. At present, the design of mechanisms with cam drives is primarily performed on the basis of well-established laws. Many authors propose to consider the motion laws of the followers according to the types: 1) dwell - rise - return - dwell; 2) dwell - rise - dwell. These laws can be represented by mathematical curves such as sinusoidal, cosine, rectilinear. Complex motion laws can be represented as consisting of simple mathematical curves combination. There are universal methods for choosing the motion laws of the follower based on the developed families of similar laws with variable parameters whose characteristics may vary widely [1-6]. The main disadvantage of these methods is the need for matching the parts of different mathematical functions in order to obtain a continuous acceleration curves. The polynomial laws of motion are devoid of this disadvantage. The degree of a polynomial is chosen so that all its coefficients can be determined from the boundary conditions. The description of such motion laws of the followers in some cases requires a high degree of the polynomial (above 10), which leads to oscillations of transfer functions and, as a result, to the deterioration of the mechanism. This method is effective only with one fixed frequency of the cam rotation. The variational method [6] can also be used to describe the motion law of the cam mechanism follower. It can only be applied in particular cases. The most appropriate (considering its universal character, ease of computer use and absence of matching) is the choice of the follower motion law described by the third-degree spline [6, 7], but in this case the process is time-consuming and requires expertise.

Therefore, the aim of the work is to develop a method for synthesizing the cam mechanism motion law which takes into account the momentum impacting the follower in the initial period of its movement.

2. Materials and methods

We use the existing experience of synthesis and introduce additional conditions based on a specific task. We propose to introduce an additional area on the cam profile which allows changing the nature of the initial movement of the cam mechanism follower. The entire synthesis process is proposed to be carried out using the mathematical package MathCAD. The cam mechanism's follower law of motion is independent of the kinematics and mechanism's structure; it is assigned by the designer.

The synthesis of the cam mechanism motion law is proposed to start with prescribing the nature of acceleration changes on a specific example. For this purpose, it is necessary to define the values of the phase angles. The stroke of the follower to the front position (rise) is assigned at 82 degrees, and to the reverse position (return) at 70 degrees. Notably, an additional displacement at 12 degrees is assigned to the follower in the forward position. The phase angle of the additional motion is selected based on the value of the period of free oscillations of the system. Then, the total cycle of the mechanism movement is 152 degrees.
Law of motion synthesis is proposed to start without considering the elastic properties of the mechanism. We carried out the synthesis of the cam mechanism at a frequency of rotation $n = 240 \text{ min}^{-1}$ in MathCAD. In the first stage of synthesis, the acceleration curve at the rise and return phases is described by the cycloidal law. This is done to simplify the accounting for the influence of large-scale factors. Further, using the acceleration matrix, the law of motion was changed: we added an area at the beginning of the cam mechanism movement. In addition, the following conditions were observed in the synthesis of the acceleration law:

- the acceleration function should be continuous (without first and second-type breaks);
- the acceleration curve should be smooth;
- the equality of the positive and negative areas of the acceleration curve must be observed.

To achieve the research goal, we made a matrix of acceleration values on the basis of the proposed law depending on the rotation angle of the cam shaft. The matrix further underwent cubic spline interpolation. The requirement of the positive and negative areas equality of the acceleration curve was observed in the matrix. The use of cubic spline interpolation allowed avoiding the problems that occur when the synthesized functions are combined.

3. Results and discussion

We presented the general methodology and approach to synthesizing the mechanism laws of motion. It can be exemplified by the synthesis of the motion law for the cam mechanism using an additional area intended for suppressing the momentum arising at the initial movement of the follower. The basic parameters for synthesis are: follower stroke $H = 0.025 \text{ m}$; phase angle $\beta = 70^\circ + 12^\circ$ (the curve angle); where $12^\circ$ is an additional angle, but that of an independent curve providing the given kinematic characteristics at the initial movement of the follower. The reverse movement of the mechanism is $\beta = 70^\circ$. The cycloidal law is taken to be the basic law for the displacement of the follower to the front position and for its reverse movement at the first stage of the synthesis. The acceleration curve corresponding to this law is shown in Figure 1.

This curve has two positive and two negative sections, so beats can be observed when the forced oscillations overlap with the natural system frequencies excited by the momentum impact at the time of the accelerations sign change; in this case, the image of the overall accelerations will be significantly distorted. Therefore, we proceed as follows: we make a matrix of acceleration values, which is drawn from the curve shown in Figure 1. Working with this matrix, we achieve the form of the curve shown in Figure 2. As a result, we obtain accelerations curve in which two negative segments were replaced by one, which enabled creating the most stable dynamic law. The resulting curve with overlapping frequency characteristics is not given due to the large variety of values.

![Figure 1](image1.png) ![Figure 2](image2.png)

**Figure 1.** Acceleration curve corresponding to the cycloidal motion law of the follower

**Figure 2.** Adjusted acceleration curve
The curve presented in Figure 2 cannot be used for further work due to the lack of equality between the areas of positive and negative sections. Therefore, using the “Trace” option (in the MathCAD environment), we compose a matrix of acceleration curve values and then scale, paying attention to obtaining a smooth and continuous acceleration curve (Figure 3).

To solve the task, we introduce an additional section at the initial movement and use the numerical values of the matrix to describe it. After a cubic spline interpolation we obtain the acceleration curve shown in Figure 4.

Then by integrating the given curve we obtain the laws for changing speeds and displacements (Figure 5, 6).

Using the curve, we obtained the values of the follower displacement in the range of 0-152 degrees with 5 degrees increments (see. Table 1).
### Table 1. Follower Motion Values

| №  | Cam angle φ, degrees | Follower Displacement S, mm | №  | Cam angle φ, degrees | Follower Displacement S, mm |
|----|----------------------|----------------------------|----|----------------------|----------------------------|
| 1  | 0                    | 0                          | 15 | 70                   | 23.450                     |
| 2  | 5                    | -0.130                     | 16 | 75                   | 24.619                     |
| 3  | 10                   | -0.272                     | 17 | 80                   | 25.134                     |
| 4  | 15                   | -0.293                     | 18 | 85                   | 24.934                     |
| 5  | 20                   | -0.109                     | 19 | 90                   | 24.033                     |
| 6  | 25                   | 0.499                      | 20 | 95                   | 22.451                     |
| 7  | 30                   | 1.743                      | 21 | 100                  | 20.208                     |
| 8  | 35                   | 3.684                      | 22 | 105                  | 17.363                     |
| 9  | 40                   | 6.312                      | 23 | 110                  | 14.256                     |
| 10 | 45                   | 9.825                      | 24 | 115                  | 10.534                     |
| 11 | 50                   | 12.970                     | 25 | 120                  | 7.252                      |
| 12 | 55                   | 16.309                     | 26 | 125                  | 4.494                      |
| 13 | 60                   | 19.296                     | 27 | 130                  | 2.458                      |
| 14 | 65                   | 21.682                     | 28 | 135                  | 1.127                      |

We have carried out the necessary calculations and built a cam profile for implementing the proposed law. The values of the radius vector of the cam profile in the specified range are determined by the formula:

\[ \rho(\phi) = \rho(0) + s(\phi), \]

where \( \rho(0) \) is the minimum radius vector of the cam profile; \( s(\phi) \) is the follower displacement.

During the dwell period (153–360 degrees), the values of the radius vector are constant and equal to a minimum value of 90 mm.

### 4. Conclusion

The work suggests the methodology for synthesizing the cam mechanism motion law which takes into account the momentum impacting the follower in the initial period of its movement.

We proposed to introduce an additional area on the cam profile which allows changing the nature of the movement of the cam mechanism follower at the initial period of its movement in order to suppress the momentum arising at this time.

Using the proposed methodology, we have developed the cam mechanism motion law which provides more stable conditions for the mechanism in terms of its dynamics. The calculations are expressed in numerical values and presented in the form of a cam profile table.

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