Structural-parametric synthesis of mechanisms in CAD-systems

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Abstract. The article describes the methodology of structural-parametric synthesis of mechanisms using CAD-tools of computer-aided design. This approach makes it possible to reduce the time required to develop mechanisms schemes for specific engineering solutions and to calculate approximate values already at the development stage of the kinematic scheme. In the mechanism synthesis, one of the main tasks is to determine the operating space and the mechanism output link motion. Using CAD programs to determine the parameters of kinematic schemes reduces design time, and the use of animation functions allows one to visualize the synthesis process.

1. Introduction
The synthesis of multi-link efficient machinery mechanisms is a complex and multi-criteria task, consisting of two main stages: selecting a circuit and determining design parameters. Further technical development of engineering products in order to increase its quality characteristics is impossible without improving machine research methods, increasing the reliability of mechanism elements, improving the accuracy of calculations, and also without developing new methods for synthesizing mechanisms.

To calculate the mechanism configuration, special computer programs are most often used that require special programming skills and knowledge. Designed limited groups of specialists; they often do not reach specific users and have no practical application. General-purpose programs, such as Mathcad PTS or Microsoft Excel, considered in [1, 2], are used primarily to study the kinematic properties of mechanisms. Studies on the automated synthesis reveal mainly the issues of gear geometry for determining the optimal gear parameters and determining the cam mechanism profile [3, 4, 5]. This topic is also relevant in the designing robotic systems and mechanisms with a parallel structure [6, 7]. The use of computer-aided design systems, such as T-FLEX CAD, based on the principles of parametric modeling, enables for a given structure of the designed device to select the values for the parameters of the constituent elements, at which the characteristics are within the limits set by the developer. The advantage of using CAD software for design is that the model variables defined during the synthesis can be used for further 3D design, which allows one to edit already created models.

This work shows the principle of structural-parametric mechanism synthesis, and also considers one of its stages - determining the operating space parameters using CAD tools for parametric modeling for mechanisms of various configurations.
2. Structural and parametric synthesis

The development of automatic design systems (CAD programs) entails a transition from parametric synthesis to structurally parametric, i.e. to designing a mechanism according to given parameters, taking into account given structural features. The main difference between structural and parametric synthesis is the determination of the structure during the synthesis process, as well as the possibility of changing it at various stages of design, in order to obtain a system with parameters that meet the requirements of the customer to the highest degree. The process of mechanism synthesis with the possibility of such adjustments is the integration of knowledge derived from different spheres: basic engineering knowledge, programming, design automation, the use of artificial intelligence systems, CASE tools, etc (figure 1).

![Diagram showing the relationship between knowledge areas in structural-parametric synthesis.](image)

**Figure 1.** The relationship between the knowledge areas in the structural-parametric synthesis.

Structural-parametric synthesis of mechanisms can be represented as a diagram (figure 2). Structural synthesis takes into account the number of degrees of mobility of the mechanism \( W \), the number of movable links \( n \), the types of kinematic pairs \( p \), the type of mechanism (L-linkage, C - cam, G - geared, LG - geared-linkage, R - robotic, PL – parallel-kinematic, etc.), and also takes into account freedom of the space in which the mechanism functions (XYZ or XY).

The operation of the mechanism depends, first of all, on the number of degrees of freedom, which determines the number of variations in the ratio of the number of links and kinematic pairs without passive joints and unnecessary mobility. In general, the formula for determining the number of kinematic pairs can be represented as:

\[
(6-m)n-W = \sum_{i=1}^{i=m\cdot5} (6-m-i)p_{(6-i)}
\]

where \( m \) – number of common links imposed \( m = 0,1,2,3,4 \), \( W \) – number of degrees of freedom, \( n \) – number of movable links.

For example, for a flat four-link mechanism with one degree of freedom, there are 4 different combinations of kinematic pairs incorporate pairs of types 4 and 5, and when taking into consideration the type of pair (\( p_5 \): turning, sliding or screw), the number of options increases manifold. To narrow
the field of finding solutions, the number of pairs of type 5 can be limited. The relationship between links and kinematic pairs is clearly demonstrated by a method based on theory of graphs [8, 9, 10]. The mechanism is represented in the form of a graph in which the kinematic pairs are edges and the links are its vertices.

**Figure 2.** Model of structural-parametric synthesis of mechanisms.

Parametric synthesis is directly related to structural, since the type of mechanism determines the most important characteristics associated with the geometry and operation of the mechanism as a whole. For example, for mechanisms with parallel kinematics, the size of the operating space can be chosen as the main synthesis parameter, for gear mechanisms, the gear ratio, and dynamic characteristics play an important role in robotics. When designing, one selects the main synthesis parameter, the rest are considered additional.

It should be noted that each type of mechanism has its own set of parametric characteristics. Obtaining the desired trajectory of the output link of multi-link mechanisms is an urgent task in the design of mechanical systems of various configurations: with a closed and open kinematic chain, single-circuit and multi-circuit structure, with one and several degrees of freedom. But sometimes, in order to achieve a given trajectory of links, it is necessary to sort through many different variations of structural solutions before finding one that satisfies all the parameters. This task requires considerable time, and the solution chosen by the designer is not always optimal and precisely meets the stated requirements. To reduce the time spent on synthesis, methods of visual-parametric design are helping.

### 3. Visual and parametric synthesis in CAD systems

When designing link mechanisms, the use of CAD tools to solve synthesis problems greatly simplifies the task of finding optimal solutions. The ability to visualize the result of the synthesis using animation allows one to see the synthesized mechanism in operation and adjust the necessary sizes. This technique is useful when the structure of the mechanism is initially unknown, but there are, for example, restrictions on the trajectory of the output link.
3.1. Synthesis of a double-stroke mechanism

Figure 3. Kinematic diagram of the synthesized mechanism (a) and structural graph (b).

An example of using T-Flex CAD to perform the synthesis task is shown for a mechanism with a double-stroke rocker arm, the output link of which makes two moves with different angular measures $\gamma_{S1}$ and $\gamma_{S2}$ (basic synthesis parameters) in a single revolution of the initial link. The mechanism has a closed bypass structure, as can be seen in figure 3 (b), and has one degree of freedom.

Figure 4. Output span angles, depending on various link lengths of the synthesized mechanism.

The synthesis task is to determine the ratio between the links of the mechanism in order to ensure the maximum value of the span of the link 5 close to 180° and the minimum possible value for the second section of the output link, while the time taken to implement the move of a larger angle should be much less than the travel time of a small angle.

Using the capabilities of parametric modeling and the ability to visualize the process of working the mechanism through animation, the ratio of the lengths of the links for the figure 4 were obtained. It was found that obtaining the required law of motion is possible under the following conditions: the lengths of the links 5 and 4 are equal or differ slightly, and the distance $DE$ is close in value to the length of the rocker arm 3. On the basis of this, the main parameters of the model were selected: link lengths l4 and l5, as well as the coordinate determining the position of the hinge E.
3.2. Determination of parameters affecting the working area of the output link of the mechanism with two degrees of freedom

The visual parametric synthesis technique can also be used to determine the operating space of mechanisms with several degrees of freedom. When modeling the position of the output link of a mechanism with two degrees of freedom (figure 5a), the function of the position of the output link is a function of several generalized coordinates - the rotation angles of the leading links 1 and 2: 

\[ S_K = f(\varphi_1, \varphi_2) \]  

The study found that the position of the output coordinate and the trajectory of the output link in complex closed multi-circuit mechanisms depends not only on the geometric parameters of the links and the choice of the structural scheme, but also on the direction of rotation of the driving cranks. With equal values of geometric dimensions, it was determined that the operating space of the point K is more extensive with the opposite direction of the angular velocities of the driving links. The result of visualizing the process of the working mechanism in the T-Flex CAD program is shown in figure 5 (b-c).

\[ \varphi_1 \]

\[ \varphi_2 \]

\[ K \]

\[ f \]

\[ w_1 = w_2 \]

\[ w_1 = -w_2 \]

**Figure 5.** Modelling of the operating space of the mechanism with two degrees of freedom (a - scheme of the mechanism, b - trajectory of the point K at \( w_1 = w_2 \), c - trajectory of the point K at \( w_1 = -w_2 \)).

4. Consequences

The following results were obtained:

- computer-aided parametric design systems can serve as a tool for solving the problems of structurally parametric synthesis of machine mechanisms;
- the proposed structural-parametric synthesis algorithm determines the procedure for determining the parameters of the mechanism during the synthesis;
- study of the characteristics of multi-link mechanisms with a given structure and a different number of degrees of mobility with CAD design tools allows one to determine which of the parameters of the mechanism affects the synthesis result in the most way, which makes it possible to maximize the synthesis output parameters to those set by the customer.
The creation of new mechanisms and the development of structural-parametric synthesis techniques using modern technologies is an urgent task of modern engineering. Using CAD tools and other automation tools enables to make the synthesis process effective and increase the efficiency of the mechanisms.

References
[1] Evgrafov A N and Petrov A N 2017 Lecture Notes in Mechanical Engineering pp 45-56
[2] Chernaya L A 2017 Kinematic and Kinetostatic Study of Flat Lever Mechanisms using Mathcad and Autocad systems (Moscow: The Bauman Universitet Publishing House)
[3] Brovkina Yu I, Sobolev A N and Nekrasov A Ya 2019 Lecture Notes in Mechanical Engineering 9783319956299 1169-79 doi: 10.1007/978-3-319-95630-5_122
[4] Sobolev A N and Nekrasov A Ya 2016 Russian Engineering Research 4 300-2
[5] Balabina T A, Brovkina Yu I and Mamaev A N 2019 Lecture Notes in Mechanical Engineering 9783319956299 2027-2035 doi: 10.1007/978-3-319-95630-5_218
[6] Glazunov V A, Rashoyan G V, Aleshin A K, Shalyukhin K A and Skvortsov S A 2020 Advances in Intelligent Systems and Computing 902 683-91
[7] Brovkina Yu I, Sobolev A N and Nekrasov A Ya 2017 Vestnik MSTU Stankin 1(40) 52-6
[8] Egorov O D and Buynov M A 2016 Vestnik MSTU Stankin 1(36) 71-4
[9] Dobryanskii L and Freindshtein F 1967 Engineering design and technology 1 180-7
[10] Levizkii N I 1990 Theory of Mechanisms and Machines (Moscow: Nauka)
[11] Smelyagin A I 2002 Proc. Int. Conf. on 5th International Symposium on Science and Technology (Korea-Russia) pp 257-61