Tendencies of non-assur mechanisms use in the structure of technological machines

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Abstract. The article gives the scientific research analysis results in the field of non-assured mechanisms on the basis of which the conclusion is made about the need for further development of mechanisms and methodological approaches to the synthesis of machines with special properties of the kinematic structure. This makes it possible to reduce energy consumption and improve technical performance, in particular, grinding machines and presses with gear and jagged actuating devices. The developed general scheme for the formation of the adaptable parameters of the technological machine establishes the dependence of these parameters on the conditions determined by the external environment, the properties of the initial and final product, and also implements the design of a materials grinder with different physical and mechanical properties, a press for molding fuel granules based on gear and jagged actuating devices with tense closed kinematic contours. The results of experimental studies have confirmed the existence of a relationship between the magnitude of the closed kinematic loop prestressing and the energy of the grinding and pressing process. The revealed regularities make it possible to minimize energy consumption in accordance with the strength of the mill charge or the size of the deformed sample by choosing rational parameters of the circuit stress, i.e. to adapt the technological machine to the properties of the processed material. Experimental studies of a gear mill on a sample of sandstone, quartz, marble have confirmed that, with the same energy consumption, the maximum grinding efficiency (an increase in the proportion of fine particles) is achieved only in a certain range of closed kinematic circuit loading corresponding to the strength of the mill charge. The data obtained make it possible to use the effect of a tense closed kinematic contour of gear and jagged actuating devices in technological machines for various purposes.

1. Introduction
The variety of processed materials properties, the variability of technological processes and operations determine the variety of technological machines and equipment: mankind responded to each new technological need by creating a new device.

If we consider the path of machines development, then initially they were represented as something single and integral (a mill, a ship, etc.), intended for some operation or type of work. Over time, it became clear that machines, used in different areas of life, have many similarities, the same functional blocks. For example, the drive, transmission mechanism, working body. The division of the machine into parts according to their functional characteristics was very hard for the humanity and took a long time. Functional and structural diagrams used in modern design practice are still not unambiguous.
The division of the machine into individual elementary mechanisms, kinematic pairs, links, the classification of mechanisms by the function of transforming motion are usually associated with the names of Gaspard Monge and Lazare Carnot. Perhaps this was one of the first attempts to systematically present the theory of the simplest machines and their elements. This division made it possible to make more accurate calculations in static and then dynamic modes. The foundations for the development of the of mechanisms structure and classification theory belong to F. Reuleaux and L.V. Assur [1].

F. Reuleaux introduced the concepts of a kinematic pair and a kinematic chain, and L.V. Assur developed the classification and principles for constructing mechanisms. However, mechanisms formed by the layering of normal type chains (the so-called normal kinematic chains that do not have excess or missing leads) were taken into consideration. This approach introduced certain restrictions. The classic task of the mechanisms analysis is to identify "extra" kinematic connections and their elimination, which simplified the determination of the number of the degrees of freedom, the calculation of the kinematics and dynamics of the mechanism.

However, the kinematic chains of positive and negative orders, which were later called non-assure kinematic chains, continued to be used in the practice of designing complex mechanisms, giving them special properties and confirming the generally accepted pattern of technical systems development - the pattern of structure complication, the number of elements and connections. So, any technological machine based on a certain physical principle (effect) in its development becomes more complex due to quantitative and qualitative changes, first of all, kinematic chains. Structural formations theory development was not included in the Assur classification.

Particular interest in non-assure mechanisms manifested itself in the second half of the 20th century, which is confirmed by numerous studies in the field of structural theory: adaptive and indifferent mechanisms [1, 2], mechanisms with anomalous structure [3], mechanisms with a negative degree of freedom (static) [4], mechanisms with a tense closed loop [5], mechanisms with a variable structure [6, 7], etc.

In the above theories, structures of mechanisms that were not included in the classical theory of L.V. Assur are considered. The existence and possibility of using such mechanisms in technology was also pointed out by L.V. Assur in his doctoral thesis [1]: "In addition to the mechanisms formed by layering of a normal type chains, there can and indeed be mechanisms formed by chains with excess and missing leashes. These mechanisms drop out of the study, since the study of such chains would complicate the classification and introduce complete uncertainty into it. "Later V.I. Tainov [8], considering anomalous structures of mechanisms, called them "isotopic".

2. Materials and methods of non-assured mechanisms research in the structure of grinding machines with toothed working bodies

The variety of terminology indicates the need for the structural formations’ theory development, methodological approaches to their study and their classification. Today the above studies have resulted in creation of specific machines that use the special properties of mechanisms to improve technological or technical performance.

So, for example, in [6, 7] mechanisms that can change the number of links of kinematic pairs and their mobility, inertial and elastic parameters, variety and reunification of kinematic chains are considered. So, “mechanisms based on the constancy of the structure can be divided into two groups: mechanisms of constant and variable structure” [8].

For the first time mechanisms with variable structure were considered in the works of E.Ya. Antonyuk and S.N. Kozhevnikov [9, 10]. They were further developed in the studies of S. Abdraimov, T.O. Nevenchanaya [6, 7, 11] and others. Numerous designs of impact machines used in construction and mining, technical machines in light industry, etc. were developed on the basis of the created classifications and mechanisms synthesis methods. Further classification showed the presence of two types of basic links: constantly attached to other links and periodically connected to other links.
Sets of basic elementary solutions of mechanisms, built according to strict formal criteria are given in work [4] in a systematic form - the form of a catalog. However, the limitations in the classical theory of L.V. Assur do not allow taking into account all the variety of possible design solutions included in the catalogs. In this regard, K. Roth notes [4]: "In order to be able to describe any (including static) structures, we will also apply the concept of "chain" to single-link pairs ...". He also concludes: "chains with the number of links of the degrees of freedom \( f \leq 0 \) are called here" static ", and kinematic - with the number of degrees of freedom \( f \geq 0 \). That is, in the catalog with \( f = -1 \), static circuits can be suitable for use as fasteners and fixed connections. The "statically stressed cycle" is a closed chain of links \( f = -1 \), and the force effect is carried out not only through the working surfaces, but also through the working volumes, i.e. processing objects.

Kutzbach [12], Hein [13] and many other authors in their works pointed to the expediency of using "stressed cycles" in "paired connections". The effective use of tense closed kinematic circuits (contours) is realized in wear test stands, in sampling gaps mechanisms, etc. The works [5,14] present the results of a systemic machine mechanisms consideration using tense closed circuits. The mechanisms proposed in [5, 14] were developed and implemented in machines for grinding and cutting various materials, pressing equipment, energy-saving and energy storage drives of construction, lifting and mining machines, etc. According to the proposed classification, mechanisms were investigated with preliminary loading, with variable loading of kinematic variable structures.

Most of the studies [2, 15, 16, 19, 20–23], developing the theory of mechanisms systematization, consider the basic classification of L.V. Assur, which is the main, central core of the general classification. So, in work [16] V.V. Dobrovolsky calls the mechanisms formed by chains with excess and missing leashes, "non-assur chains of positive and negative orders," depending on whether they increase or decrease the number of degrees of freedom and by how many units. In the works of L.T. Dvornikov [17] the proposed by him general (universal) structural classification was complemented and analyzed with non-assur mechanisms.

Substantiated approaches to the synthesis of adaptive and indifferent mechanisms [1, 2] made it possible to obtain a number of fundamentally new technical solutions in various industries, to confirm the advantages and prove the effectiveness of non-assur mechanisms of both positive and negative orders.

From the point of view of the structural theory, adaptive or non-assur chains of positive orders are chains that have “a greater number of mobility degrees than the number of leading links per the number of adaptive links of a given mechanism that connect its driven links in a certain way” [1]. The introduced concept - an adaptive connection - is a condition for the interaction of two moving links on their relative displacement, in which their movement is not determined by either kinematic or dynamic parameters of the mechanism, but depends only on the parameters of the technological (working) process [1]. This makes it possible to automatically regulate the operation of the machine as a whole or its units, depending on external conditions, to redistribute the installed power between the executive bodies in a given way. Research questions and the introduction of adaptive mechanisms were carried out by G.M. Vodyanik, E.V. Rylev, A.N. Drovnikov and others.

The presence of non-assur groups of negative orders in the structure of the mechanism causes the appearance of opposite properties: immunity, indifference to the magnitude of the closing connection. By analogy with adaptive mechanisms, the concept of an indifferent connection is introduced, i.e. closing connection, which reduces the mechanism degree of freedom, but does not reduce its mobility. If the adaptive structural group has an “extra” link that serves the development of a closed contour of the kinematic chain, then in an indifferent mechanism this link forms a new closed loop, serves to increase the number of contours. In this case, the tensile or compressive force applied to the "extra" link cannot be brought to the output link, which makes it possible to create an interference fit in it.

A number of presses and other equipment mills designs developed on this basis by A.N. Drovnikov, S.A. Kuznetsov, V.S. Isakov, V.B. Balashov et al. are given in [18].
3. The results of non-assur mechanisms studies in the structure of grinding machines with gear working bodies

Grinding of various natural and technological materials is a mandatory process in almost all industries: mining, coal, chemical, etc. In agriculture and woodworking industry, about 100 million tons of biological waste are left annually, which are also grinded during subsequent processing. Thus, physical properties, chemical compositions of materials are characterized by a variety and a wide range of values. At the same time, some physical properties, for example, the strength of particles change with an increase in the thickness of grinding. The structure of new composite materials is characterized by the heterogeneity of the individual inclusions’ properties: strong, brittle, viscous, etc.

Therefore, the ideal shredder structure should be one that adapts to the physical properties of the starting material. An adaptation in this case means adjustment to the properties of the destroyed material by introducing certain changes in the design (reconfiguration, replacement of individual elements, structural changes or in another way) in order to increase the efficiency and reduce the energy consumption of the process. Such changes can be made through the use of adaptive, indifferent and other mechanisms structures discussed in section 1 of this article. Existing mechanical shredders with gear working bodies, in our opinion, are the most suitable for these requirements.

The general diagram of the adaptable parameters is shown in Figure 1.

![Figure 1. Formation of adaptable parameters](image-url)

As it can be seen from the presented diagram, the parameters of the initial and final product determine the design features of the grinder working body, determine the need for changes (adaptation), and also directly affect the adaptable parameters. Generally, the conditions that determine non-adaptation can be represented by three groups: changes in the size of the original
product, changes in requirements to the final product. Each group requires adequate changes in one or a set of adaptable parameters.

The increase in the size of the initial product determines the size of the mill inlet, the size of the teeth and possibly the center-to-center distance in order to arrange the pre-grinding degree. The requirements for the final product determine the profile (shape) of the teeth, the center-to-center distance, the organization of the recycle, and for mills with closed kinematic loop [5] and the value of prestressing. Changes in the physical properties of the initial product correspond to changes in the size and profile (shape) of teeth, center-to-center distance, the addition of special (for example, cutting) elements, etc. Each change presupposes the presence of dominant methods of destruction. Shredders with a toothed (toothed) working body are able to implement various methods of destruction: crushing, breaking, impact, abrasion, cutting, etc. It is advisable to choose the dominant methods depending on the requirements for the final product and the type of material.

Singling out (Figure 1) the strength of the destroyed material from the whole variety of physical properties, it can be assumed that the main adaptable parameter will be the amount of preliminary compression of the stressed closed kinematic contour. By determining the correct stress for different materials, you can maximize mill efficiency.

4. The results of experimental studies on mechanisms with a tense constantly closed kinematic circuit.

The purpose of experimental studies is to confirm the influence of design factors on the operating properties of the actuator, the presence of a relationship between the closed circuit voltage and the efficiency of the mechanism, determining the amount of prototype shrinkage depending on the load of the closed stressed circuit and the load on the drive, as well as determining the amount of work expended on deformation of the prototype, depending on varying factors.

The general view of the laboratory stand with a stressed permanently closed kinematic circuit is shown in Figure 2.

**Figure 2.** External view of the laboratory stand with a tense closed kinematic loop

Two blocks are installed on fixed supports. Involute teeth are installed respectively on the handles rigidly fixed to the blocks. The involute engagement allows rolling with minimal slip.

The distance between the supports of the blocks is chosen equal to two radiuses of the pitch circle.

To create the load that simulates the voltage of a closed kinematic loop, the blocks are interconnected by means of a chain, and the load value can be changed stepwise from 25 to 120 kg.

Lead shot with a diameter of 3; 3.9; 4.7; 4.9 mm is chosen as processing objects. Before the start of the experiment, the shot underwent a visual control for spherical shape and instrumental control for
diameter deviation. The admissible value of the diameter deviation is no more than 1%. The material of the object is chosen in accordance with the fact that it deforms plastically, elastic deformations are minimal.

The process of crushing the prototype is carried out by installing it between the teeth, the installation is carried out in such a way that the pressure on it is produced at the point of teeth contact. Additional voltage is gradually installed on the platform of the block, changing in steps of 100 g until the system starts to move. The teeth, rolling towards each other, crush the sample and interlock. The amount of the prototype shrinkage was determined with a micrometer. The spread of the reading did not exceed 6%. The test results are summarized in Table 1, describing the magnitude of the loading, the thickness of the sample after deformation, the force required to actuate the mechanism, the linear shrinkage of the material, the magnitude of the relative shrinkage, the volume of the test specimen, the deformed volume and the magnitude of the relative change in volume.

| $m$, kg | 25 | 50 | 75 | 100 | 112.5 | 25 | 50 | 75 | 100 | 112.5 |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| $H_i$, mm | 4.05 | 2.80 | 1.71 | 1.60 | 1.43 | 3.89 | 2.80 | 1.80 | 1.52 | 1.40 |
| $Q_H$, mm | 43.8 | 96.9 | 175 | 188 | 193.7 | 43.2 | 88.8 | 160.5 | 182.3 | 190.3 |
| $D$, mm | 0.85 | 2.10 | 3.19 | 3.30 | 3.47 | 0.81 | 1.90 | 2.90 | 3.18 | 3.30 |
| $\Delta V$, mm$^3$ | 2.62 | 25.5 | 30.6 | 35.5 | 35.4 | 2.28 | 11.53 | 24.66 | 28.91 | 0.532 |
| $\frac{\Delta V}{V_0}$, mm$^3$ | 0.043 | 0.236 | 0.498 | 0.528 | 0.575 | 0.042 | 0.212 | 0.454 | 0.532 | 0.567 |

5. Analysis of the experimental studies results.

By the amount of information, the conducted experimental research gives an idea of use effectiveness of the closed-loop power mechanisms.

The increase in the value of the relative shrinkage $\frac{\Delta V}{D_0}$ is accompanied by a corresponding increase in the additional effort (Figure 3).

Points 1, 2, 3, 4, 5 show the value of the initial load mass (for the sample with $D_0 = 4.9$ mm). That is, with an increase in the weight of the load over 150 kg, the work efficiency increases slowly. For the sample with $D_0 = 3.0$ mm with the same weight of the load, the process is carried out more intensively. Thus, for objects of different diameters and different physical nature, the magnitude of the effective stress of the closed loop is different. Point 2 corresponds to a weight of 50 kg; an additional drive force is 96.9 N.
Figure 3. Dependence of the relative shrinkage value on the driving force

According to the obtained data, it is possible to calculate the specific work, that is, the work spent on deformation of 1 mm$^3$.

With the same weight for a sample with a diameter of $D_0 = 3.0$ mm, the additional drive force is 75.2 N.

From a linear shrinkage value, you can go to a more accurate characteristic - the value of the deformed volume $\Delta V$, which can be calculated by the formula:

$$\Delta V = \frac{1}{6} \cdot \pi \cdot \left( \frac{D_0}{2} - \frac{1}{2} \cdot H_1 \right) \left[ 3 \cdot \left( \frac{D_0^2}{4} - \frac{1}{4} \cdot H_1^2 \right) + \left( \frac{D_0}{2} - \frac{1}{2} \cdot H_1 \right)^2 \right].$$

And we calculated the amount of work required to deform a given volume (Figure 3, 4 and Table 2).

Figure 4. Change in work spent on volume change for samples of different shapes
Figure 5. Influence of contour preloading on the amount of work per 1 mm$^3$ of the deformed volume

Table 2. The results of calculating the work per 1 mm$^3$ of the deformed volume (for the model of the mechanism)

| $m_F$, kg | $\Delta V$, mm$^3$ | $A$ | $A/\Delta V$ |
|----------|-------------------|-----|-------------|
| 25       | 1.374             | 12  | 8.73        |
| 50       | 5.408             | 52.9| 9.78        |
| 75       | 8.354             | 124.0| 14.84      |
| D$_0$ = 3.0 mm |                  |       |             |
| 25       | 2.8               | 21.1| 7.55        |
| 50       | 12.53             | 102.7| 8.2        |
| 75       | 17.94             | 199.8| 11.14      |
| D$_0$ = 3.9 mm |                  |       |             |
| 25       | 2.28              | 14.9| 6.54        |
| 50       | 11.53             | 76.5| 6.63        |
| 75       | 24.66             | 246.9| 10.01      |
| D$_0$ = 4.7 mm |                  |       |             |
| 25       | 2.62              | 16.2| 6.18        |
| 50       | 14.55             | 97.3| 6.69        |
| 75       | 30.66             | 303.6| 9.90       |

The comparison of pressing processes on a model and in a press in terms of energy costs is incorrect, since the press stress has only a vertical direction, and when pressing on involute teeth the tangent component will also take place. However, it is possible for comparison in terms of technical efficiency of the two pressing technologies, on involute teeth and in a press.

For this purpose, samples were obtained on a press with a shrinkage value ($\Delta$) corresponding to the samples pressed on a model.

The growth rate of work spent on 1 mm$^3$ of deformed volume for the press is much higher than for the model. The ratio of the amount of work spent on the model for the same deformations is shown in Figure 6.
- for $D_0 = 3.0 \text{ mm}$
  $\Delta = 0.80; 1.68; 2.16 \text{ mm}$;
- for $D_0 = 4.9 \text{ mm}$
  $\Delta = 0.85; 2.10; 3.19 \text{ mm}$

**Figure 6.** The ratio of the amount of work spent in the press to the amount of work spent on the laboratory bench

The work when pressing the sample $D_0 = 3.0 \text{ mm}$ up to the shrinkage $\Delta = 2.16 \text{ mm}$ using the experimental stand is 32 times less than the work expended by the press. In general, the ratio of works ranges from 10 to 32 times. Thus, the proposed technology of pressing (or grinding) on machines with a permanently closed stressed structure formed by gear drives has a significant economic and technical effect. The presence of tangential stresses on the deformed sample, rolling of the working surfaces can significantly reduce the energy consumption of the process. The value of the circuit rational stress depends on a number of factors: the geometric dimensions of the processing object, the physical properties of the material, etc. Therefore, for each specific case, the magnitude of the circuit voltage, the engagement profile and the parameters of the mechanism must be determined individually, which confirms the validity of the theoretical development of the generalized method for calculating the mechanisms given in Chapter 2.

Based on the results of the research, the design of the mill was developed, shown in the diagram (Figure 7).

The graphs (Figure 8) show the change in the granulometric composition of the material crushed in a mill without loading a closed kinematic loop and with preliminary loading. The volume of particles of larger fractions decreases, and the volume of particles $> 0.15 \text{ mm}$ increases with the same energy consumption for grinding. In addition, the grinding time is sharply reduced. The presented data confirm the efficiency of using a mill with a stressed closed kinematic loop.

Comparative bar diagrams presented in Figure 9 serve as a more visual form of the results presentation. The increase in the mass of fine fractions is highlighted in the graphs. The maximum increase in the percentage of particles with a size of 0.15-0.315 mm is 7.8% for sandstone. In crushed quartz and marble, the main increase in the mass of small particles occurs in the range $> 0.15$: 8% and 4.52%, respectively.
Figure 7. Gear-pin mill with a tense closed kinematic circuit: 1 – motor; 2 – gearbox; 3 - differential couplings; 4 - working body fixed on the hollow shaft 6; 5 - working body fixed on the inner shaft 7; 8 - body mills; 9 - lantern wheel

Sandstone
(compression resistance 78,5 MPa)
Figure 8. Diagrams of the material granulometric composition crushed in the mill.
Figure 9. Granulometric distribution diagrams after grinding in a mill
6. Conclusion
The results obtained, firstly, confirmed the operability and efficiency of strained closed kinematic circuits’ application in mills with a gear (toothed) working body. Secondly, they showed that the efficiency of crushing and pressing is determined by the magnitude of the closed kinematic loop prestressing, set in accordance with the physical and mechanical properties of the material being processed.

Having carried out experimental studies on the laboratory bench and the developed gear-pin mill, it was possible to obtain the rational loading forces of the closed kinematic loop in relation to different ranges of the crushed materials strength (Figure 10) in mills equipped with a gear (toothed) working body.

![Figure 10. Rational forces of loading a closed kinematic loop](image)

Based on the results obtained in the process of grinding materials, confirming the operability and determining the rational loading range of a closed kinematic loop, using gear (toothed) working bodies, it becomes possible, in addition to grinding or cutting various kinds of materials, to use this technical solution to obtain fuel granules. As in the case of grinding, the manufacture of fuel pellets is a very energy-intensive process that requires an optimal squeezing force of the starting material for the best molding, and the use of the proposed system will significantly reduce the energy consumption in the process of obtaining fuel pellets with the possibility of implementing a sufficient force during molding.

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