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FRACTAL VICE: HISTORY, VARIETIES, THEORETICAL STUDIES, CREATION CONCEPTS HISTORY

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ABSTRACT

For the first time, the scientists of the Igor Sikorskyi KPI have comprehensively revealed questions related to the history and theoretical research of fractal vices and various types of other universal vices that perform universal functions when clamping objects of complex shape. Modern software products and modeling methods are used in the theoretical research.

1. INTRODUCTION

In practice, vices with two kinematic chains, including differential helical gears, are already used. In these designs, the first kinematic chain is designed to select the gap between the workpiece and the jaws due to a manual or mechanized drive, and hydraulic and electromechanical converters are used as the second kinematic chain. But there are still no theoretical foundations for the creation of locksmith and machine vices, which are built using a genetic-morphological approach. In practice, the use of little-known designs of universal vices, in which it is possible to clamp workpieces of various shapes without changing the clamping jaws. A long time ago, an invention [1] was patented in the USA with a manual drive and screw transmission based on the principle used in the mathematical theory of fractals.

Known works performed at KPI named after Igor Sikorsky, on the use of the system-morphological approach and modern methods of finding new technical solutions for the creation of vices with specified or improved functional capabilities [2]. Previously conducted research was devoted to the strength and stiffness characteristics of machine vices, as well as the use of fluid and bulk media in clamping elements, but there is no single methodological approach to the design of universal vices [3, 4]. There are well-known studies carried out in Bulgaria [5, 6].

2. VARIETIES

The inquisitive mind of Man is trying to find original solutions for creating vices with non-traditional clamping jaws (rubber, plastic, liquid, fractal, pin, folding, etc.) for clamping objects of any shape. Below are examples of such vices (Fig. 1-3).

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Fig. 1. Making clamping jaws of vices in the form of fractal elements

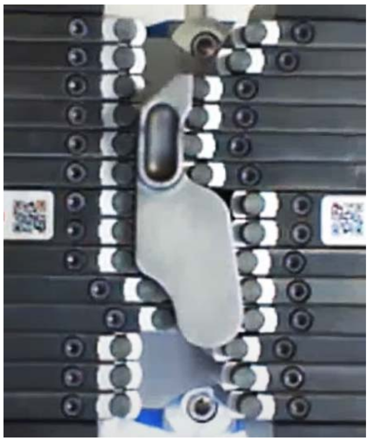

Fig. 2. Example of vices with finger jaws

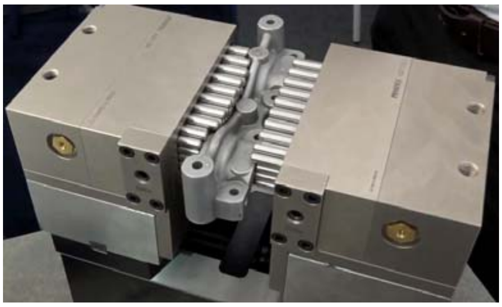

Fig. 3. Example of vices with pin jaws

3. THEORETICAL RESEARCH

Relevance of the research topic.

Mechanical engineering and metalworking have always required the ability to process parts that have complex shapes and go beyond traditional bodies of rotation or bodies limited by parallel and perpendicular planes. In addition to the problem of manufacturing such parts, there is the problem of fixing them on a metal cutting machine for further processing. One of the ways to solve this problem is the use of fractal vises [1]. The statement [2] that fractal vices are practically absent on the machine tool market needs some clarification. These vices are sometimes found among the offers of some marketplaces, however, in fact, the offer is extremely limited, so general and specialized Internet search engines may not detect them. The largest Chinese marketplace AliExpress actually offers two models of fractal vices, the design of which corresponds to US patent No. US1059545A [7]. Vises [8] (Fig. 4) are made of structural steel and represent a machine tool that is intended for use in industry in conditions of repair and single production.

Fractal vices [6] (Fig. 2) have essentially the same design, but are made of stainless steel and have some secondary differences that do not affect functionality. Both vise designs have 4-level fractal jaws. The vise [5] (Fig. 3) has a somewhat simplified design compared to the previous two. They have 3-level fractal sponges and are made of aluminum alloy. These vices are considered practically unsuitable for use in heavy engineering and metalworking, however, they can be used in hobby activities. The considered fractal vices are non-mechanized and have a manual clamp drive. That is, unsuitable for use in automated production. Also, a common negative feature of the presented fractal vices is their high cost. As of the time of writing the article, the cost of vices was as follows (Table 1).

Table 1 *Comparison of the cost of fractal vices (approximate values)*

Fractal vise model Price	*Price, USD*		
	Product	*Delivery*	*General*
4-level structural steel vise	*7304*	*311*	*7615*
4-level stainless steel vise	*4171*	*445*	*4616*
3-level aluminum alloy vise	*1678*	*415*	*2093*

Source: developed by the authors

Fig. 4. Industrial fractal vises made of structural steel
Source: https://a.aliexpress.com/EGbo3EN

Fig. 5. Industrial stainless steel fractal vise
Source: https://a.aliexpress.com/ExwSmKh

Fig. 6. Amateur fractal vise made of aluminum alloy
Source: https://a.aliexpress.com/Ew1hdZL

Thus, the cost of fractal vices (which are just a machine tool, moreover, non-mechanized, with a manual drive) is commensurate with the cost of the milling machine itself (not only on the secondary, but also on the primary market) and is considered unreasonably overpriced. The extremely high price is incomprehensible, since no expensive materials are used in the construction of fractal vises, and the surfaces of the details of these vises are described by typical surfaces (planes, cylinders, cones, etc.), i.e., such surfaces that were available for metalworking at the beginning of the 20th century at the time of their patenting. However, it is quite possible that in the near future there may be such favorable circumstances in the industry that the fractal vise will receive a "second life", as it happened with many other inventions and technical solutions. For example, a muzzle-loading rifle is seen as an anachronism in the 21st century, however, today it is manufactured by some leading manufacturers as a premium segment hunting weapon [9]. Therefore, further research of such an interesting technical object as a fractal vice along with other universal vices with a very likely perspective of a significant expansion of their application in the foreseeable future is expedient.

4. FORMULATION OF THE PROBLEM

On the other hand, fractal vises and their modeling are of considerable academic interest. Fractal vices with their part clamping scheme occupy a somewhat intermediate position between traditional vices with two clamping elements (parallel jaws) and original vices [3], in which the clamping elements are made in the form of elastic containers filled with some compression-resistant substance, which when clamped with a complex profile details seem to envelop it according to Pascal's law. If we abstract from a three-dimensional model to a flat one, then with some assumptions and conventions, we can assume that fractal sponges interact with the detail also according to Pascal's law. At the same time, it is assumed that after clamping the part, the sponges acquire the properties of a certain monolith [2] and interact with the fixed part not only by means of normal reactions, but also by frictional forces at the point of contact of the end elements of the sponges with the surface of the part. That is, a rather complex clamping scheme is created, in which there is no final clarity as to how the process of mechanical processing of the part fixed in the vise will behave. The aim of the study. The purpose of the research at this stage is to determine the main provisions of the virtual experiment plan, which consists in mathematical modeling of the processing of a complex profile part installed in a fractal vice. The modern tool for visual simulation of dynamic systems Simulink [10] from the MATLAB package is proposed for use. Research results. Previously, a flat mathematical model [2] of mechanical processing (milling) of a complex-profile part fixed in a fractal vice with some preliminary assumptions was proposed. The presented mathematical model is based on the calculation scheme (Fig. 4).proposed. The presented mathematical model is based on the calculation scheme (Fig. 7).

The mathematical model is a system of three differential equations of the second order (1), which describe plane-parallel displacements of the processed part in the XY plane and torsional displacements relative to the Z axis.

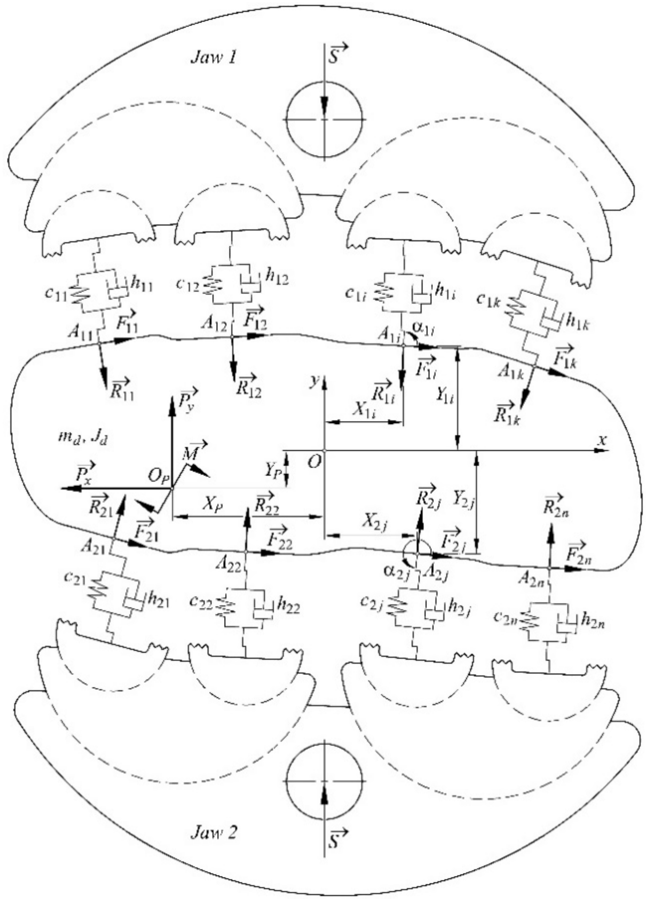

Fig. 7. The resulting calculation scheme for processing a complex profile part, installed in a fractal vise

Source: developed by the authors

$$
\begin{cases}
m_d \cdot \ddot{x} + \sum_{i=1}^{k} R_{1i} \cos\alpha_{1i} + \sum_{j=1}^{n} R_{2j} \cos\alpha_{2j} + \sum_{i=1}^{k} F_{1i} \cdot \sin\alpha_{1i} + \sum_{j=1}^{n} F_{2j} \cdot \sin\alpha_{2j} = P_x(t) \\
m_d \cdot \ddot{y} + \sum_{i=1}^{k} R_{1i} \sin\alpha_{1i} + \sum_{j=1}^{n} R_{2j} \sin\alpha_{2j} + \sum_{i=1}^{k} F_{1i} \cdot \cos\alpha_{1i} + \sum_{j=1}^{n} F_{2j} \cdot \cos\alpha_{2j} = P_y(t) \\
J_d \cdot \ddot{\varphi} + \sum_{i=1}^{k} R_{1i} \cdot \sin\alpha_{1i} \cdot (X_{1i} + x) + \sum_{i=1}^{k} R_{1i} \cdot \cos\alpha_{1i} \cdot (Y_{1i} + y) + \sum_{i=1}^{k} F_{1i} \cdot \sin\alpha_{1i} \cdot (Y_{1i} + y) + \\
+ \sum_{i=1}^{k} F_{1i} \cdot \cos\alpha_{1i} \cdot (X_{1i} + x) + \sum_{j=1}^{n} R_{2j} \cdot \sin\alpha_{2j} \cdot (X_{2j} + x) + \sum_{j=1}^{n} R_{2j} \cdot \cos\alpha_{2j} \cdot (Y_{2j} + y) + \\
+ \sum_{j=1}^{n} F_{2j} \cdot \sin\alpha_{2j} \cdot (Y_{2j} + y) + \sum_{j=1}^{n} F_{2j} \cdot \cos\alpha_{2j} \cdot (X_{2j} + x) = \\
= M(t) + P_x(t) \cdot (Y_P + y) + P_y(t) \cdot (X_P + x)
\end{cases}, \quad (1)
$$

where

$$
\begin{cases}
R_{1i} = h_{1i} \cdot \sqrt{\dot{x}^2 + \dot{y}^2} + c_{1i} \cdot \sqrt{x^2 + y^2} + \frac{S}{k} \\
R_{2j} = h_{2j} \cdot \sqrt{\dot{x}^2 + \dot{y}^2} + c_{2j} \cdot \sqrt{x^2 + y^2} + \frac{S}{n}
\end{cases} \quad (2)
$$

$$
\begin{cases}
F_{1i} = R_{1i} \cdot f \\
F_{2j} = R_{2j} \cdot f
\end{cases}. \quad (3)
$$

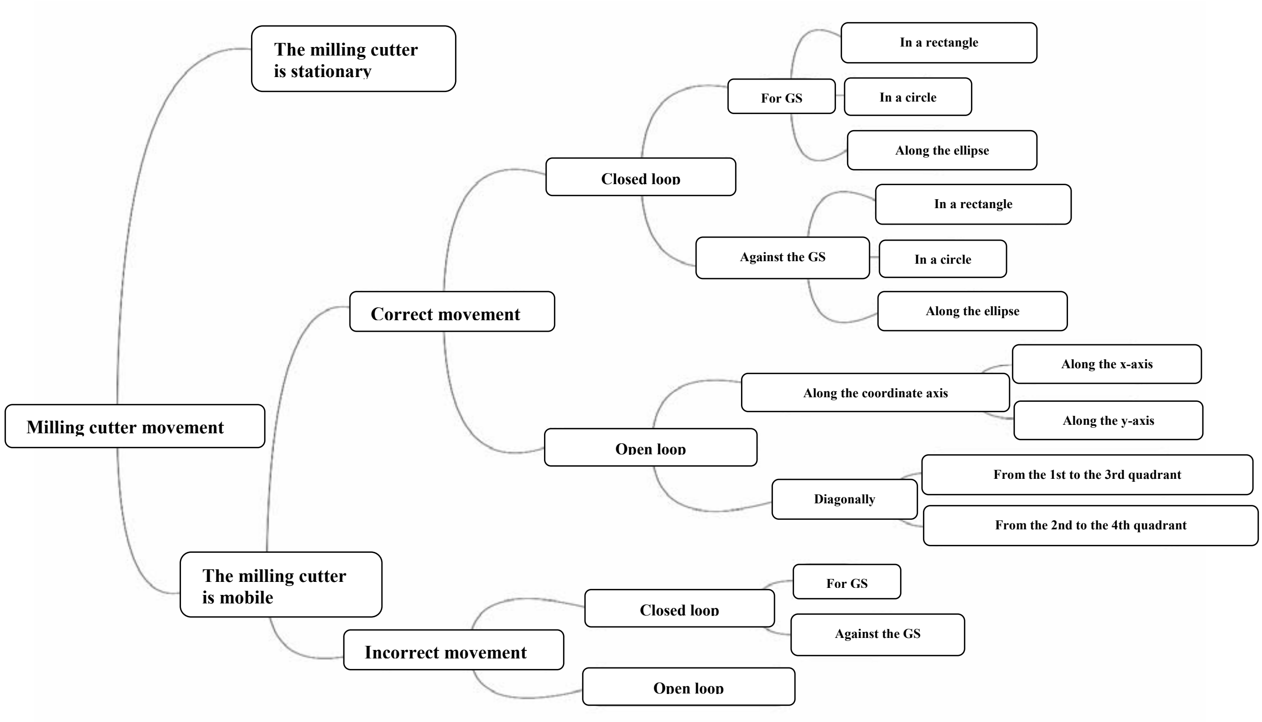

Fig. 8. Variants of milling cutter movement in the context of mathematical modeling Source: developed by the authors

The explanation of the elements of the mathematical model - the components of the formulas (1...3) is given in the table. 2. The presented mathematical model is to some extent universal - it assumes a theoretically unlimited number of levels of fractal sponges. However, in order to rationally use the available computing resources, according to the authors, it should be limited to 3 (as in Fig. 4) or 4 fractal levels. Firstly, this number of levels corresponds to the design of real vices presented on the industrial equipment market. Second, the smaller number of levels (1 or 2) nullifies the advantages of fractal vices.

Table 2 *Elements of the mathematical model and their recommended values*

Elements	***General designation***	***Dimensionality***	***Value***
The mass of the part	m_d	*kg*	*1…5*
The moment of inertia of the part	J_d	*kg·m²*	*0,5…1,5*
Clamping force	S	*N*	*3 000…5000*
The number of final sponges of the first and second fractal sponges	k, n	*б/р*	$k = n = 4$
Coordinates of contact points of end jaws and details	X_{1i}, Y_{1i} X_{2j}, Y_{2j}	*m*	*are determined after clamping the part*
Orientation angles of the end jaws at the points of contact with the part	α_{1i}, α_{2j}	*рад*	*are determined after clamping the part*
The resulting cutting force along the X axis	P_x	*N*	*1000…3000*
The resulting cutting force along the Y axis	P_y	*N*	*2000…5000*
Cutting moment	M	*N·m*	*100…500*
Coordinates of the point of application of force factors of the cutting process	X_P, Y_P	*m*	*are determined after clamping the part*
Reaction forces of end lips at contact points	R_{1i}, R_{2j}	*N*	*var*
Frictional forces between the end jaws and the surface of the part at the contact points	F_{1i}, F_{2j}	*N*	*var*
Coefficient of friction at the contact points	f	*б/р*	*0,3*
Coefficients of elasticity of end jaws at contact points	c_{1i}, c_{2j}	*N/m*	*20000…50000*
Damping coefficients of end jaws at contact points	h_{1i}, h_{2j}	*N·s/м*	*are determined by analogy*
Displacement of the part along the X axis	x	*m*	*var*
Displacement of the part along the Y axis	y	*m*	*var*
Angular displacement of the part relative to the Z axis	φ	*рад*	*var*
Simulation time	t	*s*	*0…104*

The milling process, which is considered the main work process, in the context of mathematical modeling, is characterized by the following force factors (on the plane): – total cutting force, which is represented by orthogonal components and coming from the geometric center of the milling cutter; is the total cutting moment applied at the same point. The point itself is characterized by coordinates relative to the geometric center of the vise - point . Thus, the milling process provides the required force factors as for a flat model. The power factors of the cutting process are not constant over time, but depend on a number of random factors, in particular: – geometrical parameters of the tool (deviation of the radius of the tool, number of cutter teeth, etc.); - heterogeneity of the material of the processed part (in particular, the presence of shells); - temperature and other random processes, etc. Therefore, it is preliminarily assumed that the random deviations of the values of the power factors of the milling process will be within ±10%. The next stage of preparation for mathematical modeling is the determination of the movement of the milling cutter (Fig. 8) relative to the point.

With a fixed milling cutter, it is considered that the point is fixed, that is, its coordinates are unchanged. Instead, with a moving cutter, one or both coordinates are variable in time: – when moving along the coordinate axis, one of the coordinates is variable in time, and the other is constant; – movement along a rectangular trajectory is a combination of movements along the coordinate axes, i.e., the milling cutter goes around some predetermined rectangular contour; - movement along the diagonal implies that both coordinates change simultaneously in time. Since in universal milling machines the amount of feed is set by the control bodies of the machine and is a constant value during the milling process, it is considered that during the mentioned movements (along the axis, along the rectangle and diagonally) the coordinates change according to a linear law:

$$X_P(t) = X_{P_0} + v_x \cdot t \quad Y_P(t) = Y_{P_0} + v_y \cdot t\,, \tag{4}$$

where X_{P_0}, Y_{P_0} – some initial values, m; v_x, v_y – the cutting speed along the coordinate axes, m/s, and t is assumed that movement in a circle and ellipse, as well as irregular movement, can be realized on a CNC machine tool, while the coordinates (4) change according to a nonlinear law, i.e. and . Clockwise (CW) or counter-clockwise motion is relevant in the context of counter or parallel milling. At the same time, it is considered that in all cases the cutter rotates in the "positive" direction, that is, "counter-clockwise". In all variants of movement of the milling cutter, it is considered that it does not go beyond the boundaries of the part. That is, there is no intermittent cutting, and the power factors of the milling process never reach zero values. The main purpose of the virtual experiment at this stage is to compare the specified and real trajectory of the milling cutter and analyze the influence of the parameters of elastic-damping elements, clamping force, etc. on the result. Based on the analysis of the elements of the mathematical model (Table 2), options for the movement of the milling cutter (Fig. 5) and some of the aforementioned assumptions, a morphological matrix of options for conducting a virtual experiment is compiled (Table 3).

At the same time, if in the table 2 value of the element of the mathematical model is presented in the form of a range, then it is recommended to take three variants of values for this element: – closer to the lower limit of the range; – closer to the upper limit of the range; – arithmetic mean or geometric mean value.

Table 3 *Morphological matrix of options for conducting a virtual experiment (incomplete)*

Parameter	*Value*	
1. Movement of the milling cutter	*1.1. The milling cutter is stationary* *1.2. Along the X axis* *1.3. Along the Y axis* *1.4. Diagonally from the 1st to the 3rd quadrant* *1.5. Diagonally from the 2nd to the 4th quadrant* *1.6. Against GS on a rectangle* *1.7. Against GS in a circle* *1.8. Against GS on an ellipse*	*1.9. According to GS along the rectangle* *1.10. For GS in a circle* *1.11. According to GS along the ellipse* *1.12. Against GS on the wrong closed circuit* *1.13. According to the GS in the wrong closed circuit* *1.14. By an irregular open circuit*
2. Weight of the part	*2.1. 1 kg* *2.2. 3 kg* *2.3. 5 kg*	
3. The moment of inertia of the part	*3.1. 0,5 kg·m²* *3.2. 1,0 kg·m²* *3.3. 1,5 kg·m²*	
4. The resulting cutting force along the X axis	*4.1. 1000 N* *4.2. 2000 N* *4.3. 3000 N*	
5. The resulting cutting force along the Y axis	*5.1. 2000 N* *5.2. 3500 N* *5.3. 5000 N*	
6. Cutting moment	*6.1. 100 N·m* *6.2. 300 N·m* *6.3. 500 N·m*	
7. Clamping force	*7.1. 3000 N* *7.2. 4000 N* *7.3. 5000 N*	
8. Feedback	*8.1. Missing (unlocked model)* *8.2. Available (closed model)*	

The technological system "machine - vice - tool - workpiece" is a closed dynamic system with negative feedback [4]. However, as a virtual experiment, a small number of studies should be conducted with the open system (without feedback) and then compared with the rest of the studies. Even such an incomplete matrix provides more than 20,000 options for conducting a virtual experiment. Therefore, conducting a one-factor experiment is impractical and actually impossible in view of the time spent and the rational use of available computing power. To conduct a multifactorial experiment, 10 most characteristic combinations of parameters are pre-selected:

$$X_1 = 1.4 - 2.3 - 3.3 - 4.3 - 5.3 - 6.3 - 7.1 - 8.2$$
$$X_2 = 1.5 - 2.3 - 3.3 - 4.3 - 5.3 - 6.3 - 7.3 - 8.2$$
$$X_3 = 1.6 - 2.3 - 3.3 - 4.3 - 5.3 - 6.3 - 7.1 - 8.2$$
$$X_4 = 1.9 - 2.3 - 3.3 - 4.3 - 5.3 - 6.3 - 7.3 - 8.2$$
$$X_5 = 1.4 - 2.3 - 3.1 - 4.3 - 5.3 - 6.3 - 7.1 - 8.2$$
$$X_6 = 1.5 - 2.3 - 3.3 - 4.1 - 5.3 - 6.3 - 7.3 - 8.2$$
$$X_7 = 1.6 - 2.3 - 3.3 - 4.3 - 5.1 - 6.3 - 7.1 - 8.2$$

$$X_8 = 1.9 - 2.3 - 3.3 - 4.3 - 5.3 - 6.3 - 7.1 - 8.2$$

$$X_9 = 1.4 - 2.3 - 3.3 - 4.3 - 5.3 - 6.3 - 7.1 - 8.1$$

$$X_{10} = 1.9 - 2.3 - 3.3 - 4.3 - 5.3 - 6.3 - 7.3 - 8.1$$

The appropriateness of one or another parameter will be determined by the availability of real machine tools, tools, equipment and consumables, which will determine the actual experiment and the comparison of its results with the results of the virtual experiment.

5. CONCLUSION

Theoretical and experimental research on universal vices, which allow clamping objects of arbitrary shape, are relevant and should be continued. This will solve the scientific and technical problem of expanding the technological and functional capabilities of metal cutting machines of the drilling and milling group.

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