Parameter Identification of Fixtures Based on Artificial Neural Networks and Regression Analysis for Ensuring the Efficient Machining

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Abstract – The paper presents the scientific approach for the comprehensive use of computational intelligence systems, numerical simulation data, and mathematical modeling using regression procedures for identification parameters of the complicated mechanical system "machine tool – fixture – cutting tool – workpiece". The developed methodology is realized in the example of a flexible fixture for fork-type parts machining. As a result, the dependencies between the system of clamping and cutting forces/moments and corresponding generalized displacements of points/surfaces are obtained. The proposed methodology allows evaluating the maximum value of displacements for a workpiece under the influence of clamping and cutting forces and moments. The developed methodology is clarified using an artificial neural network for the case of significant nonlinearities in contact interactions between functional elements of the considered system. Finally, the reliability of the developed approach is proved experimentally with the maximum relative error of about 1 %. Since the permissible tolerance is equal to 21 μm, the obtained result ensure the reliability of the proposed design scheme of the mechanical system "fixture – workpiece".

1. Introduction

One of the most important problems in the field of up-to-date manufacturing engineering is to increase the competitiveness of products. This problem can be solved by optimizing of the production indicators by means of the implementation of flexible fixtures, modern machining centers, and cutting tools.

Due to the highly developed multiproduct manufacturing, there is a need in relatively frequent readjustments for machining parts of another row. Therefore, it is advisable to design fixtures with the possibility of automated readjustment for fixturing of constructively similar parts within the required technical characteristics.

Moreover, before starting the manufacturing process, it is necessary to determine the flexibility of the system "fixture – workpiece" for further evaluation of its efficiency. For this purpose, a new method of calculating the stiffness of functional elements should be developed. Particularly, such technique will be able to determine the influence of clamping and cutting forces and moments on the stiffness of the comprehensive mechanical system "fixture – workpiece", as well as to consequent optimization of the designed fixture to improve the machining performance and reduce costs of its manufacturing.

2. Literature review

Up-to-date CAFD systems are actively used for fixture design to reduce the preparation and manufacturing time [1], as well as to increase the flexibility of fixtures in multiproduct manufacturing [2]. In this case, the fixture design procedure is carried out generally in three stages: development of the design scheme, analysis, and consequent optimization.

The research works devoted to solving the first stage are mainly focused on facilitating the design and reduction of the influence of human factor during the fixture design. The most popular approaches to solving this problem are based on the precise analysis of independent situations [3–6] using the recently developed methods [7].

The second stage of the fixture design is realized using the analysis of deformations and contact interactions between functional elements of the system "fixture – workpiece" by means of artificial neural networks and the Box–Wilson experimental design method [8, 9].

The works devoted to solving the third stage are mainly focused on optimizing the spatial positioning of locating and clamping elements by the use of artificial neural networks and genetic algorithms both separately [10–15] and comprehensively [16, 17]. The particle swarm method [18, 19], the method of precedent reasoning [20], and analysis of the interaction between functional elements of the mechanical system "fixture – workpiece" [21] are additionally used.

Moreover, there are papers describing a complete cycle of the fixture design by the combined use of genetic algorithms and artificial neural networks [22], as well as by the combined use of artificial neural networks and experiment planning [23]. In these papers, the main attention is paid to the analysis and minimization of deformations of a workpiece. Additionally, ways for using integrated approaches for optimal fixture layout design are presented in the research works [24–28].

The main disadvantages of recent research data include the lack of evaluation and optimization of clamping and cutting forces/moments. Moreover, the comprehensive methodology for designing CAFD systems is not developed yet.

3. Research methodology

The proposed approach allows studying a flexible fixture for a row of parts/workpieces performing only one simulation using the finite element method. The consequent determination of displacements is performed according to the obtained analytical dependencies to identify the permissible clamping and cutting forces/moments.

The essence of the developed methodology is to determine the impact of clamping and cutting forces/moments on linear and angular displacements of a workpiece using the previously evaluated weigh factors.

The methodology is divided into three stages: calculation of static displacements as a result of clamping forces and moments; determination of dynamic displacements as a result cutting forces and moments); evaluation of total displacements as a result of comprehensive action of clamping and cutting forces/moments.

There are input data for calculation: 3D model of a fixture and a workpiece; physical characteristics of the clamping elements of the fixture (clamping forces and moments); physical characteristics of the cutting tools for fixture machining (cutting forces and moments).

The determination of static displacements begins with a matrix of static displacements:

$$v_{i0} = \sum_{j=1}^{m} \alpha_{ij} Q_j, \tag{1}$$

where α_{ij} – weight factors ($i = 1, 2, \ldots, N$); N – total number of measuring data; Q_j – generalized forces ($j = 1, 2, \ldots, m$); m – total number of clamping forces/moments; v_{i0} – generalized static displacements in measuring points/surfaces.

The generalized dynamic displacements are determined using the following model:

$$\Delta v_{i0} = \sum_{k=1}^{n} \beta_{ik} F_k, \tag{2}$$

where $\Delta v_i = (v_i - v_{i0})$ – generalized dynamic displacements determined as a difference between total v_i and static v_{i0} displacements; β_{ik} – weight factors ($k = 1, 2, \ldots, n$); n – total number of cutting forces/moments.

The weight factors α_{ij} and β_{ik} are evaluated as a result of numerical simulation using the following regression dependencies:

$$\alpha_{ij} = \frac{v_i\left(F_j = 0\right)}{Q_j}; \ \beta_{ik} = \frac{\Delta v_i\left(Q_j = 0\right)}{F_k}. \tag{3}$$

The total values of generalized displacements are determined as a sum of the corresponding static and dynamic displacements:

$$\Delta v_{i0} = v_{i0} + \Delta v_i = \sum_{j=1}^{m} \alpha_{ij} Q_j + \sum_{k=1}^{n} \beta_{ik} F_k. \tag{4}$$

It should be noted that the following inequality is required for ensuring the implementation of the regression procedures for the consequent evaluation of clamping and cutting forces: $N \geq (m + n)$.

4. Results

4.1. Fixture design

For the use of the 3D model within the CAE system, the 3D model of a fixture should be preliminary designed and optimized. For this purpose, it is necessary to remove the structural elements (i. e. chamfers, roundings, grooves, places under the internal hexagon), which do have a significant impact on the fixture's stiffness, but can decrease the machining time due to reducing the mesh size.

As a result, the following clamping devices are used in the designed flexible fixture: two pneumatic cylinders, and a wedge mechanism which is powered by a pneumatic cylinder (Figure 1).

Compact pneumatic cylinders “Festo ADNGF-63-50-PPS-A” are used for clamping V-blocks by the nominal force $F_{pl} = 1.87$ kN. The wedge mechanism includes a compact cylinder “Festo AEN-63-20-I-P-A” with the nominal force $F_{pl} = 1.74$ kN.

The force from a plunger $F_{pl} = 0.5F_{pr}\text{ctg}(\alpha/2)$ directly acts on a workpiece through the wedge mechanism, where α is an angle of the wedge. Particularly, for the case of $\alpha = 20°$, the following value can be calculated: $F_{pl} = 4.93$ kN.

The values $F_c = 1.74$ kN and $M_c = 10.9$ N·m of cutting force and moment, respectively, were chosen using the “Sandvik Coromant Tool Guide” online application for the case of preliminary drilling of 10 mm hole.

4.2. Determination of the weight coefficients for the clamping process

To determine weight coefficients, three stages of studies should be conducted. The first one is realized numerically when applying only the unit value $F_{pr} = 1$ kN of the clamping force from the V-block.

The second stage is realized analytically when applying the unit value $F_w = 1$ kN of the clamping force from the wedge mechanism.

The last stage is realized experimentally or numerically when applying the real value of the clamping force. The corresponding design schemes are realized using the ANSYS software and shown in Figure 1.

The consequent step is in measuring displacements on a surface with the maximum distance from the operating surface. The results of numerical simulation and measuring the corresponding displacements u_0 and v_0 are shown in Figure 2. The numerical simulation data are summarized in Table 1.

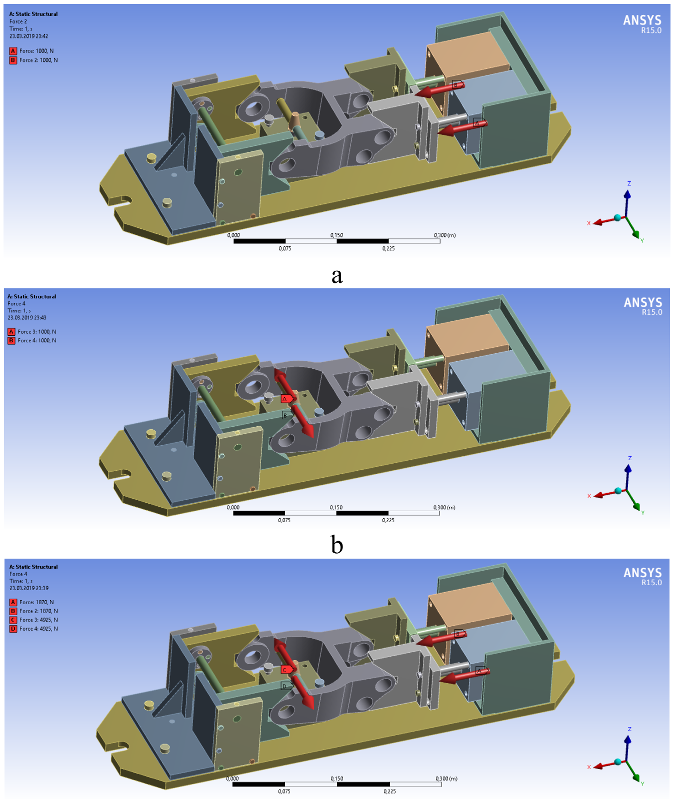
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Figure 1. The design schemes of a clamping chart during the 1st (a), 2nd (b), and 3rd (c) experiments

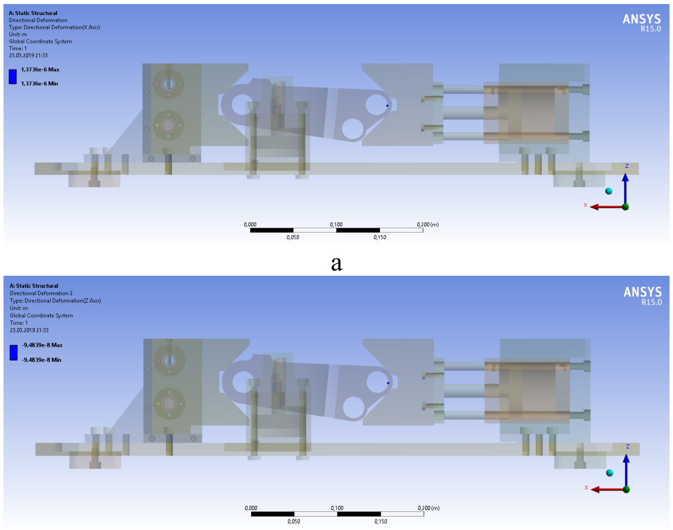
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Figure 2. The resulting static displacements u_0 (a), v_0 (b)

According to the equation (3), the weight factors are determined, mm/kN: $\alpha_{11} = 1.37$, $\alpha_{21} = -0.09$, and $\alpha_{12} = \alpha_{22} = 0$. Thus, $u_0 = 1.37F_{pr}$, $v_0 = -0.09F_{pr}$, and the maximum value of total displacements of the workpiece under the action of clamping forces is equal to $s_0 = (u_0^2 + v_0^2)^{1/2} = 2.57$ (μm). This value does not exceed the tolerance 21 μm for the hole's machining.

4.3. Determination of the weight coefficients for the cutting process

In this step, an array of weight factors is determined for cutting forces and moments. For this purpose, three more experiments should be conducted. Firstly, the actual clamping force and the unit value of cutting force $F_c = 1$ kN are applied. Secondly, the actual clamping force and the unit value of cutting moment $M_c = 10$ N·m are applied. Finally, the actual clamping and cutting forces/moments are applied. The corresponding design schemes are shown in Figure 3.

The next step is in measuring the components u and v displacements on the surface, which are located in the maximum distance from the operating surface (Figure 4).

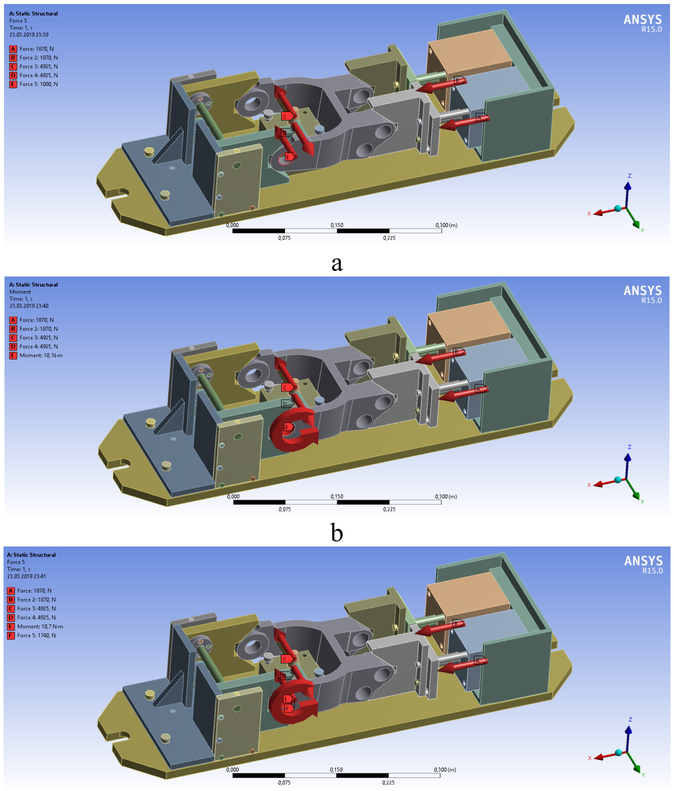
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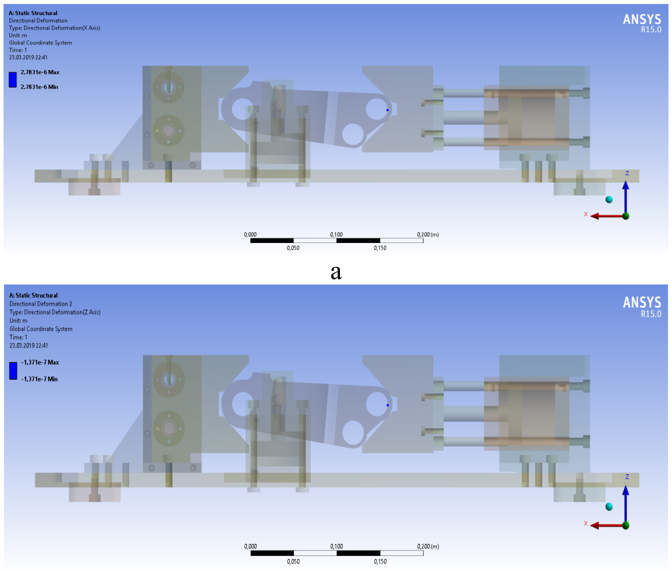
Figure 3. The design schemes of clamping and cutting charts during the 4th (a), 5th (b), and 6th (c) experiments

Values of clamping and cutting forces/moments, as well as corresponding displacements of the workpiece, are summarized in Table 1.

Table 1. Generalized results data

Experiment no.	Forces, kN			Moment, N·m	Displacements, μm	
	F_{pr}	F_w	F_c	M_c	u	v
1	1.00	0.00	0.00	0.00	1.37	–0.09
2	0.00	1.00	0.00	0.00	0.00	0.00
3	1.87	4.93	0.00	0.00	2.58	–0.18
4	1.87	4.93	1.00	0.0	2.78	–0.14
5	1.87	4.93	0.00	10.0	2.58	–0.17
6	1.87	4.93	1.74	10.9	2.93	–0.10



a

b

Figure 4. The resulting total displacements *u* (a), *v* (b)

According to the formula (3), the weight factors are determined analytically, mm/kN: $\beta_{11} = 0.20$, $\beta_{21} = 0.04$, and $\beta_{12} = \beta_{22} = 0$.

Finally, the displacements as a result of cutting force/moment are $\Delta u = -0.02F_c$, and $\Delta v = 0.04F_c$.

The summarized displacements, μm: $u = u_0 + \Delta u = 2.91$, and $v = v_0 + \Delta v = -0.10$.

The maximum value of the total displacements of the workpiece is equal to $s = (u^2 + v^2)^{1/2} = 2.93$ (μm). This value does not exceed the tolerance 21 μm for the case of the hole's machining.

4.4. Verification of the obtained results

To justify the proposed methodology, a verification of the obtained results is performed for the case of clamping forces from the V-block $F_{pr} = 1.3$ kN and wedge mechanism $F_w = 3.0$ kN, as well as cutting force $F_c = 1.2$ kN and moment $M_c = 7.0$ N·m.

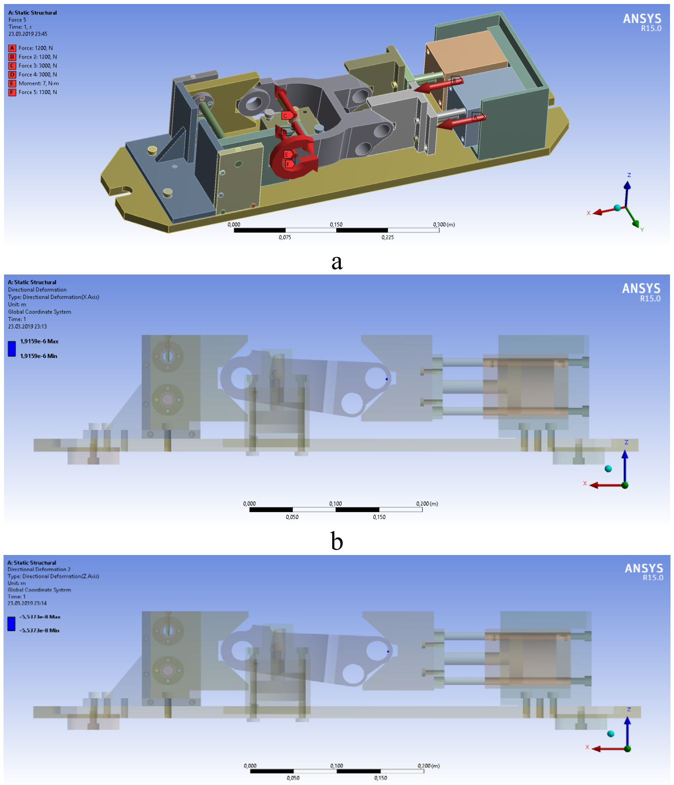
The results of the numerical simulation are presented in Figure 5.

As a numerical simulation result, the following experimental data are obtained, μm: $u_{exp} = 1.92$, $v_{exp} = -0.06$.

The corresponding values calculated using the proposed regression dependencies are $u = 1.37F_{pr} + 0.20F_c = 1.90$ (μm), and $v = -0.09F_{pr} + 0.04F_c = -0.06$ (μm).

The values obtained analytically sufficiently correspond to the values measured experimentally. In this case, the maximum relative error is equal to 1.04 %.

It should be noted that the relatively small error is due to the fact that the interaction between the functional elements of the mechanical system "fixture – workpiece" is quite linear. However, in the case of considering the significant nonlinearities in contact interactions, the abovementioned approach should be supplemented using the more precise approximation procedures, particularly, b the use of artificial neural networks.



a

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Figure 5. The loading scheme (a) and numerically determined displacements *u* (b), *v* (c)

4.5. Clarification of the proposed model using artificial neural networks

The proposed mathematical model based on the regression analysis allows considering only the linear dependencies between the displacements and external forces/moments. Due to the nonlinear contact interactions between the functional elements of the mechanical system "machine tool – fixture – cutting tool – workpiece", this approach should be clarified. One of the ways to realize this issue is in the use of artificial neural networks as universal nonlinear approximation procedures able to precise solve the most complicated problems in multidisciplinary research [29, 30].

For solving the abovementioned problem, the artificial neural network with the following parameters is designed using the Visual Gene Developer software (Figure 6): number of input parameters – 4 (clamping forces F_{pr}, F_w, and cutting force/moment F_c, M_c); number of output parameters – 2 (components *u*, *v* of summarized displacement *s*); number of hidden layers – 2; number of nodes in the 1st hidden layer – 12; number of nodes in the 2nd hidden layer – 6.

For training the network by the experimental data, the following parameters are set: transfer function – hyperbolic tangent; learning rate – $1 \cdot 10^6$; target error – $1 \cdot 10^{-5}$; initialization method of threshold – random; initialization method of weight factor – random; analysis update interval – 500 cycles.

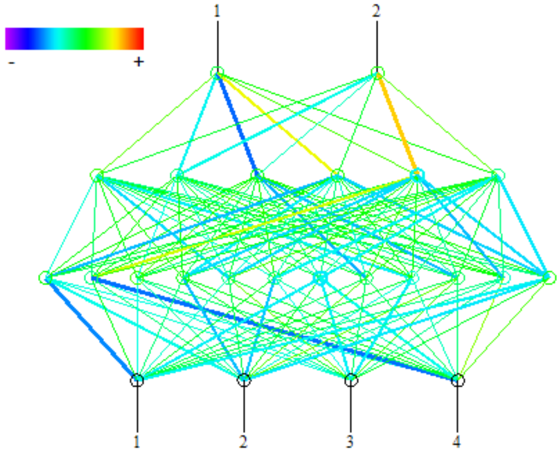

Figure 6. The architecture of an artificial neural network

As a result of training, the following parameters are reached: sum of error – $1.06\cdot10^{-4}$; average error per output per dataset – $0.89\cdot10^{-5}$; regression coefficient for the 1st output – 0.999885; regression coefficient for the 2nd output – 0.999995; slope for the 1st output – 1.0013; slope for the 2nd output – 0.9985; y-intercept for the 1st output is equal to $-1.85\cdot10^{-4}$; y-intercept for the 2nd output – $0.50\cdot10^{-4}$. The corresponding results of regression analysis are presented in Figure 7.

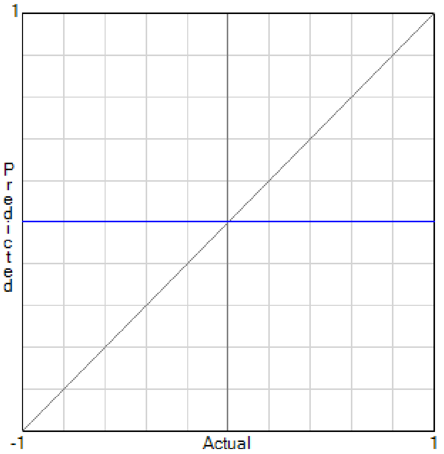

Figure 7. Results of regression analysis

As a result of using the artificial neural network, the dimensionless values of the evaluating data were obtained and summarized in Table 2.

Table 2. Dimensionless data

Data no.	**Input parameters**				**Output parameters**			
					Calculated		**Predicted**	
	1	**2**	**3**	**4**	**1**	**2**	**1**	**2**
1	0.53	0.00	0.00	0.00	0.54	0.46	0.5400	0.4600
2	0.00	0.20	0.00	0.00	0.01	0.03	0.0100	0.0300
3	1.00	1.00	0.00	0.00	1.00	1.00	0.9998	0.9976
4	1.00	1.00	0.57	0.00	0.99	0.97	0.9990	0.9699
5	1.00	1.00	0.00	0.92	1.00	0.61	0.9956	0.6101
6	1.00	1.00	1.00	1.00	0.98	0.54	0.9804	0.5400

The results show that the maximum relative error for the evaluation of output parameters is equal to 0.91 %.

5. Conclusion

In the presented research, a methodology for calculating the stiffness of fixtures is proposed. The mathematical model based on the use of the linear regression procedure is developed. The model is verified by the numerical simulation data. The proposed analytical and numerical simulation approaches are clarified using an artificial neural network. This approach allows considering nonlinearities in contact interaction between functional elements of the complicated system "machine tool – fixture – cutting tool – workpiece".

As an example, a flexible fixture for fork-type parts machining is considered. According to the evaluated data, the maximum value of 2.93 μm of total displacements is calculated for a workpiece under the influence of clamping and cutting forces and moments. Since the permissible displacement (tolerance) is equal to 21 μm, the obtained result meets the technological requirements.

As a result, the dependencies between the clamping and cutting forces/moments and corresponding deformations of functional elements of the mechanical system "fixture – workpiece" are obtained. The reliability of the proposed mathematical model is justified by the maximum relative error of about 1 % between the data obtained analytically and experimentally.

Finally, the developed methodology of the comprehensive approach using mathematical modeling, numerical simulation, and artificial neural networks allow evaluating the operating parameters of the complicated mechanical systems. The proposed approach will be useful for researchers in the field of application computational intelligence systems in manufacturing and mechanical engineering.

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