International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

September 2023 | Issue 56 | Volume 15 | Number 3 | Pages 309-315

MATRIX MODELS OF MACHINING ERRORS IN MULTI-TOOL MULTI-CARRIAGE ADJUSTMENTS

N.D. Yusubov [1] I.A. Khankishiyev [2] H.M. Abbasova [1] E.D. Mammadov [2] R.A. Huseynov [2]

1. Department of Machine Building Technology, Azerbaijan Technical University, Baku, Azerbaijan
nizami.yusubov@aztu.edu.az, abbasova.heyran@aztu.edu.az
2. Department of Shipbuilding and Ship Repair, Azerbaijan State Marine Academy, Baku, Azerbaijan
isaq.xankishiyev@asco.az, elxan.mammadov@asco.az, rasul.huseynov@dnv.com

Abstract- The article focuses on creating matrix models for machining error in multi-tool multi-carriage adjustments (setups) where tools are spatially arranged. These models take into account the elastic deformations of the technological system in all coordinate directions, along with the simultaneous impact of cutting forces from all adjustment tools. These models have been developed for both dimension distortion models and scattering field models. The workability of the developed accuracy models is shown and it is noted that the coverage of factors taken into account allows using them as a basis for a control model for multi-tool two-carriage machining and predicting the accuracy of performed dimensions.

Keywords: Machining Accuracy, Multi-Tool Machining, Error Models of Machining, Multi-Tool Multi-Carriage Adjustment (Setup), Elastic Deformations of Technological System, Scattering Field of Performed Dimensions, Linear Dimensions, Diametrical Dimensions.

1. INTRODUCTION

The accuracy of machining is heavily influenced by the elementary error Δy, which arises from the elastic displacements of the technological system caused by cutting forces. This error's value is determined by the cutting conditions and technological system characteristics, making it a critical control object that necessitates a mathematical description. A.P. Sokolovsky and K.V. Votinov established the groundwork for modeling machining accuracy. B.S. Balakshin, V.S. Korsakov, L.P. Medvedev, K.S. Kolev, and B.M. Bazrov further researched these topics [1]. The theory of machining accuracy was further enhanced by incorporating the characteristics of multi-tool and multi-carriage machining. The principles and methodology for the development of such structural mathematical models for the formation of an error in the dimensions performed under the conditions of multi-tool multi-carriage machining are formulated in the works of A.A. Koshin and N.D. Yusubov [1].

In [1], multi-tool single-carriage and double- carriage adjustments are considered, when tools are placed on one or two carriages working simultaneously. It is for these classes of adjustments, on the basis of the analytical theory of elastically deformable systems, that models of distortion of scattering fields of performed dimensions have been developed [1-3]. However, the capabilities of lathes of the turning group, designed for multi-tool machining, are much wider [4]. Entire classes of traditional machine tools - cam-driven machines-longitudinal shaped turning machines, turret lathes, cut-off machines - have more than two carriages. On automatic turret lathes and semi-automatic machines, multi-tool multi-carriage adjustments are implemented, when the workpiece is machined with tools from several transverse carriages and a set of tools from the turret, and each tool forms two dimensions - diametrical and linear (Figures 1 and 2).

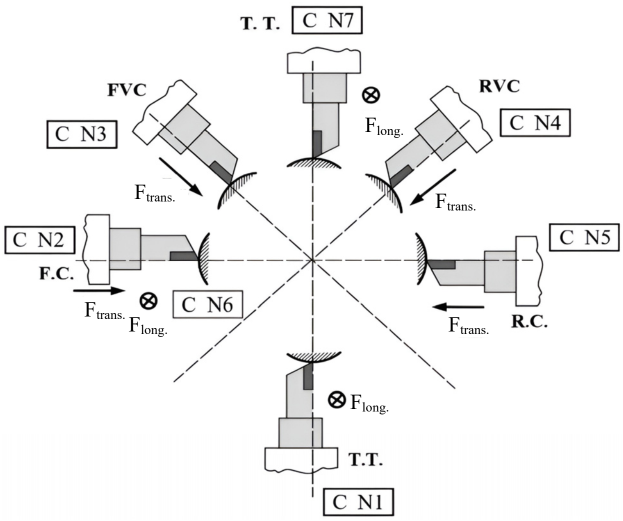


Figure 1. Multi-tool multi-carriage adjustment on automatic machines with two vertical carriages and longitudinal feed of the front carriage

It should be noted that, as practice shows, the maximum (real) number of carriages participating simultaneously in work is 3 (rarely 4). Five carriages do not work at the same time, since one carriage is always cutting off. Currently, the most commonly used adjustments are simultaneous two-carriage machining. Three-carriage adjustments are used less frequently due to the lack of recommendations about cutting conditions.

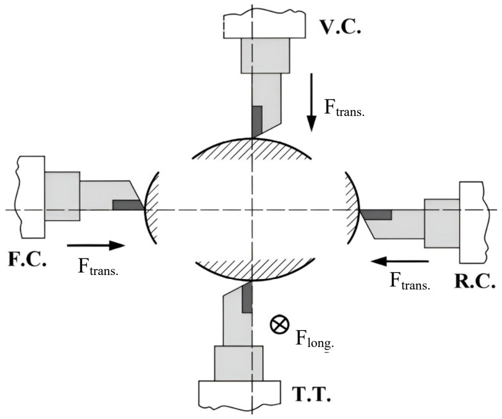


Figure 2. Multi-tool multi-carriage adjustment on automatic machines with one vertical carriage and no longitudinal feed of the front carriage

Despite the development of models for machining accuracy in multi-tool systems, a comparison with multi-tool adjustment classification reveals that many models are incomplete. Therefore, there is a need for new models that reflect the structure of multi-tool adjustment and consider all significant factors that affect the accuracy of multi-tool machining.

2. MATRIX MODELS OF DISTORTION OF PERFORMED DIMENSIONS IN MULTI-TOOL MULTI-CARRIAGE SINGLE-COORDINATE ADJUSTMENTS

To develop a mathematical model for the formation of a machining error in multi-tool adjustments, in which the number of simultaneously working carriages is more than two, we consider a generalized scheme of a multi-tool multi-carriage adjustment (Figure 3).

In the generalized multi-carriage adjustment, it is assumed that there are n carriages, the indexing of which is carried out, in accordance with the classification formula [1], by means of the variable j. It is allowed to place several tools on each carriage, the indexing of which, also according to [1], is carried out by the variable *k*. In the generalized design scheme (Figure 3), the technological system is decomposed into (*n*+1) subsystems. Each subsystem is considered in its own coordinate system: *XYZ*(0) - workpiece coordinate system (subsystem 0); $X^jY^jZ^j(0^j)$ - coordinate system of the *j*th carriage.

In accordance with this, the following designations are adopted:

- e^j $j = 0 \ldots n$ are compliance matrices of the *j*th subsystem;
- P_x^j, P_y^j, P_z^j are coordinate components of cutting forces on the *j*th carriage (in the coordinate system of this carriage);
- S_x^j, S_y^j are coordinate feeds of the *j*th carriage (in the coordinate system of this carriage);
- ζ^j is angle of rotation of the *j*th carriage (in the coordinate system of the workpiece (subsystem 0)).

In terms of analytical mechanics, the problem posed is reduced to considering the force interaction of a system of (*n*+1) bodies with elastic links.

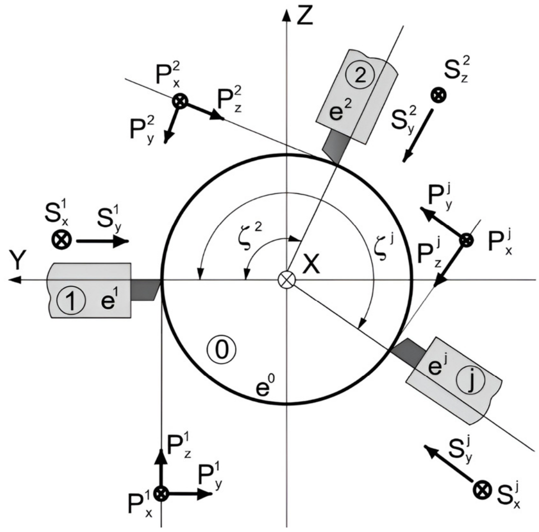


Figure 3. Generalized design scheme for multi-tool multi-carriage adjustment

From an analytical mechanics perspective, the problem at hand involves analyzing the force interaction between a system comprising (*n*+1) bodies connected by elastic links.

An analysis of the process of developing a model of the force interaction of a three-body system, described in [1], shows that an increase in the number of contacting bodies does not change the structure of mathematical models. Our concern lies in determining the displacement of the point of contact between two bodies that are in contact. This displacement is influenced by the forces acting on each body as well as the compliance of the links connecting them. Therefore, the movement of the contact point, for example, a body with index *j*=1 (subsystem 1) and a body with index *j*=0 (subsystem 0) will be determined by the following set of factors - compliance e^1 of subsystem 1 (carriage 1) and forces P_x^1, P_y^1, P_z^1 (cutting forces from the tools of this carriage) on the one hand, and compliance e^0 of subsystem 0 (workpiece) and forces applied to the workpiece, on the other hand. As such, in this case, the cutting forces from the tools of all other adjustment carriages should be considered. Therefore, the mechanism describing the formation of a machining error in a two-carriage adjustment, in the case of an adjustment of *n*-carriages, will be:

$$g_j = e^{0j}\overline{P}_j + e^0 \sum_{l \neq j} \overline{P}_l \quad (1)$$

The following notation works here:

g_j is displacement vector of the contact point of the *j*th carriage and workpiece;

e^{0j} is combined compliance matrix of subsystem 0 and subsystem *j*;

$\overline{P}_j$ is vector of cutting forces of tools of the *j*th carriage;

$\overline{P}_l$ is vector of cutting forces of tools of the *l*th carriage.

The sum is calculated over all carriages except the *j*th carriage, which is responsible for creating the particular dimension under consideration. Taking into account the designations adopted in the calculation scheme [1], the matrix model (1) can be represented in expanded form:

$$\begin{pmatrix} g_x^j \\ g_y^j \\ g_z^j \end{pmatrix} = \begin{pmatrix} e_{xx}^{0j} & e_{xy}^{0j} & e_{xz}^{0j} \\ e_{yx}^{0j} & e_{yy}^{0j} & e_{yz}^{0j} \\ e_{zx}^{0j} & e_{zy}^{0j} & e_{zz}^{0j} \end{pmatrix} \begin{pmatrix} P_x^j \\ P_y^j \\ P_z^j \end{pmatrix} + \begin{pmatrix} e_{xx}^{0} & e_{xy}^{0} & e_{xz}^{0} \\ e_{yx}^{0} & e_{yy}^{0} & e_{yz}^{0} \\ e_{zx}^{0} & e_{zy}^{0} & e_{zz}^{0} \end{pmatrix} \begin{pmatrix} \sum\limits_{j \neq l} P_x^l \\ \sum\limits_{j \neq l} \left(P_z^l \sin\zeta^l + P_y^l \cos\zeta^l \right) \\ \sum\limits_{j \neq l} \left(P_z^l \cos\zeta^l - P_y^l \sin\zeta^l \right) \end{pmatrix} \quad (2)$$

Equations (1) and (2) can be interpreted as a matrix model that describes how the dimensions produced in a multi-tool and multi-carriage system are distorted. Turning to the expanded form, we get a more transparent representation of the model, which allows us to obtain working formulas for distorting the dimensions performed in each direction of interest.

3. MATRIX MODELS OF DISSIPATION AREAS OF PERFORMED DIMENSIONS

3.1. Multi-Tool Multi-Carriage One-Coordinate Adjustments

Multi-carriage adjustments are only a quantitative extension of two-carriage adjustments [5-9]. In terms of quality, adding more carriages to the system does not alter the fundamental mechanism responsible for the formation of the scattering field of dimensions produced from the primary carriage. The combined effect of all additional carriages on the workpiece forms some resulting movement, which is superimposed on the movement of the contact point with the main carriage and, as a result, forms a distortion of the dimension being performed. Replacing the cumulative action of the system of forces from additional carriages with the resulting force, we come to the possibility of using the model of elastic interaction of the three-body system [1]. Considering this aspect, we can infer that the same mechanisms are at play in creating the scattering field of dimensions in a multi-carriage system as those observed in a two-carriage adjustment.

In double-carriage expanded adjustments, two mechanisms of formation of scattering fields of performed dimensions work. The first mechanism is activated when the force of the additional carriage is directed against the impact of the main carriage. This is an opposite adjustment, the scattering field model for it is described in [1]. The second mechanism is when the force action of the additional carriage is directed in the same direction as the effect of the main carriage. This is a non-opposite adjustment, scattering field model for it is described in [1].

When turning in multi-carriage adjustments, two types of dimensions are also formed: diametrical and linear. From models (1)-(2) we obtain the following dependencies for dimension distortion:

- Linear dimensions:

$$g_x^j = \left(e_{xx}^{0j} P_x^j + e_{xy}^{0j} P_y^j + e_{xz}^{0j} P_z^j \right) + (e_{xx}^0 \sum_{l \neq j} P_x^l + e_{xy}^0 \sum_{j \neq l} \left(P_z^l \sin\zeta^l + P_y^l \cos\zeta^l \right) + e_{xz}^0 \sum_{j \neq l} \left(P_z^l \cos\zeta^l - P_y^l \sin\zeta^l \right)) \quad (3)$$

- Diametrical dimensions:

$$g_y^j = \left(e_{yx}^{0j} P_x^j + e_{yy}^{0j} P_y^j + e_{yz}^{0j} P_z^j \right) + (e_{yx}^0 \sum_{l \neq j} P_x^l + e_{yy}^0 \sum_{j \neq l} \left(P_z^l \sin\zeta^l + P_y^l \cos\zeta^l \right) + e_{yz}^0 \sum_{j \neq l} \left(P_z^l \cos\zeta^l - P_y^l \sin\zeta^l \right)) \quad (4)$$

The following designations work here: g_x^j and g_y^j are displacement of the contact point of the *j*th (main) carriage and the workpiece in *X* and *Y* axes direction, respectively (distortions of the linear and diametrical dimensions formed from the *j*th carriage); $e_{xx}^{0j}, e_{xy}^{0j}, e_{xz}^{0j}$ are the first line of the combined compliance matrix of subsystems 0 and *j* (workpiece and *j*th carriage); e_{yx}^{0j}, e_{yy}^{0j}, e_{yz}^{0j} are the second line of the combined compliance matrix of subsystems 0 and *j* (workpiece and *j*th carriage); e_{xx}^0, e_{xy}^0, e_{xz}^0 are the first row of the compliance matrix of subsystem 0; e_{yx}^0, e_{yy}^0, e_{yz}^0 are the second line of the compliance matrix of subsystem 0; P_x^j; P_y^j; P_z^j are cutting forces coordinate components (in their own coordinate system) of the tools of the *j*th carriage (main); $P_x^l; P_y^l$; P_z^l are coordinate components of the cutting forces (in their own coordinate system) of the tools of the lth carriage (additional).

The summation is carried out over all additional carriages, excluding the main one is the *j*th carriage, at which the considered size is formed. The calculation of scattering fields is carried out considering the intervals of variation of the major technological reasons: allowances removed by each tool, strength properties of the workpiece and stiffness of technological subsystems.

Applying the methodology for constructing the dimension scattering field developed in [1] for the case of two-carriage extended adjustments, models of scattering fields of linear and diametrical dimension in a multi-carriage adjustment (5) are obtained. Equation (5) together with the introduced notation:

- Equation (6) for coordinate indices *i*;
- $\Delta j + n = w$ for cumulative scattering of the characteristics of technological system ω;
- For the influence vector of the main carriage $\overline{p}_t^j$;

$$\overline{p}_t^j=\begin{pmatrix} C_{P_x^j}t_j^{x_{P_x^j}-1}S_j^{y_{P_x^j}}v_j^{z_{P_x^j}} \\ C_{P_y^j}t_j^{x_{P_y^j}-1}S_j^{y_{P_y^j}}v_j^{z_{P_y^j}} \\ C_{P_z^j}t_j^{x_{P_z^j}-1}S_j^{y_{P_z^j}}v_j^{z_{P_z^j}} \end{pmatrix}$$

- Vector of influence of allowance fluctuations on the main carriage $\overline{p}_{\Delta t}^j$;

$$\overline{p}_{\Delta t}^j=\begin{pmatrix} C_{P_x^j}x_{P_x^j}t_j^{x_{P_x^j}-1}S_j^{y_{P_x^j}}v_j^{z_{P_x^j}} \\ C_{P_y^j}x_{P_y^j}t_j^{x_{P_y^j}-1}S_j^{y_{P_y^j}}v_j^{z_{P_y^j}} \\ C_{P_z^j}x_{P_z^j}t_j^{x_{P_z^j}-1}S_j^{y_{P_z^j}}v_j^{z_{P_z^j}} \end{pmatrix}$$

- The vector of non-opposite influence of the additional carriage $\overline{p}_{t+}^m$;

$$\overline{p}_{t+}^m=\begin{pmatrix} C_{P_x^m}t_m^{x_{Pm}-1}S_m^{y_{P_x^m}}v_m^{z_{P_x^m}} \\ C_{P_y^m}t_m^{x_{P_y^m}-1}S_m^{y_{P_y^m}}v_m^{z_{P_y^m}}\cos\zeta^m+C_{P_z^m}t_m^{x_{Pm}-1}S_m^{y_{P_z^m}}v_m^{z_{P_z^m}}\sin\zeta^m \\ -C_{P_y^m}t_m^{x_{P_y^m}-1}S_m^{y_{P_y^m}}v_m^{z_{P_y^m}}\sin\zeta^m+C_{P_z^m}t_m^{x_{Pm}-1}S_m^{y_{P_z^m}}v_m^{z_{P_z^m}}\cos\zeta^m \end{pmatrix}$$

- The vector of opposite influence of the additional carriage $\overline{p}_{t-}^m$;

$$\overline{p}_{t-}^m=\begin{pmatrix} -C_{P_x^m}t_m^{x_{Pm}-1}S_m^{y_{P_x^m}}v_m^{z_{P_x^m}} \\ -C_{P_y^m}t_m^{x_{P_y^m}-1}S_m^{y_{P_y^m}}v_m^{z_{P_y^m}}\cos\zeta^m-C_{P_z^m}t_m^{x_{Pm}-1}S_m^{y_{P_z^m}}v_m^{z_{P_z^m}}\sin\zeta^m \\ C_{P_y^m}t_m^{x_{P_y^m}-1}S_m^{y_{P_y^m}}v_m^{z_{P_y^m}}\sin\zeta^m-C_{P_z^m}t_m^{x_{Pm}-1}S_m^{y_{P_z^m}}v_m^{z_{P_z^m}}\cos\zeta^m \end{pmatrix}$$

- The vector of the non-opposite influence of allowance fluctuations on the additional carriage $\overline{p}_{\Delta t+}^m$;

$$\overline{p}_{\Delta +}^m=\begin{pmatrix} C_{P_x^m}x_{Pm}t_m^{x_{Pm}-1}S_m^{y_{P_x^m}}v_m^{z_{P_x^m}} \\ C_{P_y^m}x_{P_y^m}t_m^{x_{P_y^m}-1}S_m^{y_{P_y^m}}v_m^{z_{P_y^m}}\cos\zeta^m+C_{P_z^m}x_{Pm}t_m^{x_{Pm}-1}S_m^{y_{P_z^m}}v_m^{z_{P_z^m}}\sin\zeta^m \\ -C_{P_y^m}x_{P_y^m}t_m^{x_{P_y^m}-1}S_m^{y_{P_y^m}}v_m^{z_{P_y^m}}\sin\zeta^m+C_{P_z^m}x_{Pm}t_m^{x_{Pm}-1}S_m^{y_{P_z^m}}v_m^{z_{P_z^m}}\cos\zeta^m \end{pmatrix}$$

- The vector of the opposite influence of allowance fluctuations on the additional carriage $\overline{p}_{\Delta t-}^m$;

$$\overline{p}_{\Delta -}^m=\begin{pmatrix} -C_{P_x^m}x_{Pm}t_m^{x_{Pm}-1}S_m^{y_{P_x^m}}v_m^{z_{P_x^m}} \\ -C_{P_y^m}x_{P_y^m}t_m^{x_{P_y^m}-1}S_m^{y_{P_y^m}}v_m^{z_{P_y^m}}\cos\zeta^m-C_{P_z^m}x_{Pm}t_m^{x_{Pm}-1}S_m^{y_{P_z^m}}v_m^{z_{P_z^m}}\sin\zeta^m \\ C_{P_y^m}x_{P_y^m}t_m^{x_{P_y^m}-1}S_m^{y_{P_y^m}}v_m^{z_{P_y^m}}\sin\zeta^m-C_{P_z^m}x_{Pm}t_m^{x_{Pm}-1}S_m^{y_{P_z^m}}v_m^{z_{P_z^m}}\cos\zeta^m \end{pmatrix}$$

It represents a mathematical model of scattering areas of performed sizes in a multitool multi-carriage adjustment. This model describes the dimension scattering fields in the coordinate system of the main carriage, i.e., in the direction of the considered dimensions. To determine the scattering fields of other dimensions formed from other carriages, it is necessary to go to the coordinate system of the corresponding main carriage, which is ensured by rotating the coordinate system by the appropriate angle (Figure 3).

The index "i" here also denotes the coordinate axis of interest to us (the direction of the dimension being performed):

$$i\in\begin{pmatrix} x & y & z \end{pmatrix} \tag{6}$$

$$\Delta g_i^j=\begin{cases} \omega\left[e_i^{0j}\overline{p_t^j}t_j+e_i^0\sum\limits_{m\neq j}\overline{p_{t+}^m t_m}\right]+\left[e_i^{0j}\overline{p_{\Delta}^j}\Delta t_j+e_i^0\sum\limits_{m\neq j}\overline{p_{\Delta+}^m}\Delta t_m\right]; & e_i^0\sum\limits_{m\neq j}\overline{p_{t+}^m}t_m\geq 0 \\ \begin{cases} -\omega\left[e_i^{0j}\overline{p_t^j}t_j-e_i^0\sum\limits_{m\neq j}\overline{p_{t-}^m}t_m\right]+\left[e_i^{0j}\overline{p_{\Delta}^j}\Delta t_j+e_i^0\sum\limits_{m\neq j}\overline{p_{\Delta-}^m}t_m\Delta t_m\right] & e_i^{0j}\overline{p_t^j}t_1-e_i^0\sum\limits_{m\neq j}\overline{p_{t-}^m}t_m\leq-\frac{1}{2}\left(e_i^{0j}\overline{p_t^j}t_1\Delta t_j+e_i^0\sum\limits_{m\neq j}\overline{p_{t-}^m}t_m\Delta t_m\right) \\ \left(1+\frac{\omega}{2}\right)\left[e_i^{0j}\overline{p_{\Delta}^j}\Delta t_j+e_i^0\sum\limits_{m\neq j}\overline{p_{\Delta-}^m}t_m\Delta t_m\right] & e_i^{0j}\overline{p_t^j}t_1-e_i^0\sum\limits_{m\neq j}\overline{p_{t-}^m}t_m\leq\frac{1}{2}\left(e_i^{0j}\overline{p_t^j}t_1\Delta t_j+e_i^0\sum\limits_{m\neq j}\overline{p_{t-}^m}t_m\Delta t_m\right);\quad e_i^0\sum\limits_{m\neq j}\overline{p_{t+}^m}t_m\leq 0 \\ \omega\left[e_i^{0j}\overline{p_t^j}t_j-e_i^0\sum\limits_{m\neq j}\overline{p_{t-}^m}t_m\right]+\left[e_i^{0j}\overline{p_{\Delta}^j}\Delta t_j+e_i^0\sum\limits_{m\neq j}\overline{p_{\Delta-}^m}t_m\Delta t_m\right] & e_i^{0j}\overline{p_t^j}t_1-e_i^0\sum\limits_{m\neq j}\overline{p_{t-}^m}t_m\geq\frac{1}{2}\left(e_i^{0j}\overline{p_t^j}t_1\Delta t_j+e_i^0\sum\limits_{m\neq j}\overline{p_{t-}^m}t_m\Delta t_m\right) \end{cases} \end{cases} \tag{5}$$

The first line of the model (5) describes the scattering field under the concurrent influence of additional carriages. The second group of formulas (in the inner curly bracket) describes the case of the opposite influence of additional carriages. Three dependences in this group reflect the nature of the location of the scattering field (Figure 3 [1]):

- The second dependence describes a balanced adjustment (option 2 of the location of the scattering field [1]);
- The first and third dependencies describe unbalanced adjustment (for option 3 the first and for option 1 the third [1]).

This model is a generalization of the previously developed models:

➢ For single tool single carriage machining;

➢ For multi-tool double-carriage adjustments.

If we put m=0 in Equation (5), which means the absence of additional carriages, then we get a model for single-tool single-carriage machining. Putting m=1 (one additional carriage) and $\zeta=\pi$ (additional carriage rotated relative to the main carriage by 180°), we get a model for a deployed two- carriage adjustment [5].

For the case of multi-tool single-carriage adjustments, the scattering field model can also be obtained from Equation (5). To do this, it is enough to enter the sum of forces from all adjustment tools in the term reflecting the influence of the main carriage and put *m*=0 (no additional carriages). As a result, from Equation (5) we obtain models of scattering fields of performed dimensions for multi-tool single-carriage adjustments and homogeneous tools when machining a batch of parts.

3.2. Adequacy of Error Models

The evaluation of the adequacy of the machining error models was carried out using model experiments. Experimental studies were carried out at two levels. The first one is model experiments in laboratory conditions. On a universal equipment, a machining scheme was modeled and the influence of cutting forces on dimensional distortions due to parallel and angular displacements of the components of the technological system was experimentally evaluated. The second group of experiments was carried out directly under production conditions. However, due to the practical impossibility of readjustment of machine to process laboratory samples, this study was carried out on real factory technological processes. The study was based on methodology of statistical control of technological processes.

The conducted experimental studies have shown that the field values do not exceed the calculated values and very close to them, not going beyond the 12% interval. The calculation of accuracy parameters for several implementations, carried out in accordance with GOST 16.305-74, showed that, with a confidence probability of 0.95, the measured machining accuracy and the accuracy calculated by model (5) - for opposite and non-opposite adjustments, belong to the same general population. Thus, the adequacy of the developed models to real machining processes can be considered established.

4. THEORETICAL ANALYSIS OF THE MODEL OF MACHINING ACCURACY IN MULTI-TOOL DOUBLE-CARRIAGE ADJUSTMENTS

The resulting model for multi-tool two-carriage adjustments from (5) was tested for operability. The operability of accuracy models for multi-tool two-carriage machining is illustrated in Figure 4. Figure 4 shows how model (5) for opposite and non-opposite adjustments reflects the influence of techno-logical factors on the extent of the scattering area for diametrical sizes, performed from a longitudinal carriage for adjustment $Y_0 C_1^0(y) S_1(x)\left[u_1(y)\right] \cup Y_0 C_2^1(y) S_2(y)\left[u_9(-y)\right]$ [1].

The nature of the curves Δg_{y_1} (Figure 4) fully corresponds to what was predicted for opposite and non-opposite adjustments, i.e., has 3 branches. Three reference points are marked on the graphs:

$\circ - t_2 = 1$ mm , $\Delta - t_1 = 1$ mm , $t_2 = 3$ mm

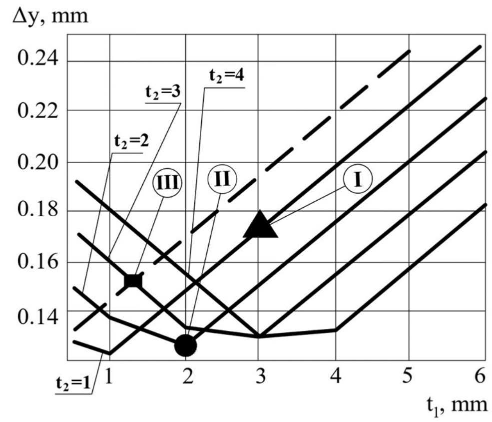
$t_2 = 1$ mm , $\Delta - t_1 = 1$ mm , $t_2 = 3$ mm

In the basic variant (Figure 4 a), for each reference point, it is indicated on which branch of the graph it is located. In variants (*b*)-(*d*) on the labels of the corresponding form, the displacements of these points relative to the base variant are shown.

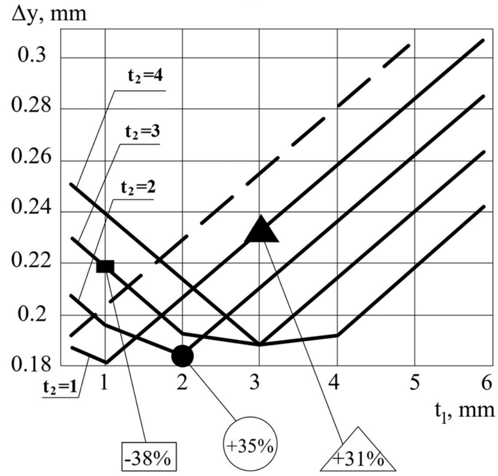
Variant (*b*) illustrates the effect of the initial workpiece error. The decrease in accuracy by one IT grade of the workpiece for the turning cutter, which directly forms the considered dimension, has almost the same effect on the diameter error is 31-38% (according to the base points) with the total action of two factors (Figure 4b). Figure 4c shows that the feed of transversal carriage has a significant effect on the dimension error generated from the longitudinal carriage - from an increase of up to 31% to a decrease of 21% at the base points.

A powerful factor is also the geometry of the cutting part of the tools (Figure 4d). Therefore, the errors at different reference points change up to a decrease of 16%. A change in the instability of the technological system (machines of different rigidity, workpieces with and without heat treatment) affects the angle of inclination of branches I and II of the graphs and, therefore, for points lying outside the balance zone, leads to a significant change in the error: from -17% to +13% (points □ and Δ), in the balance zone (point ○) influence is small: -10% to +3%.

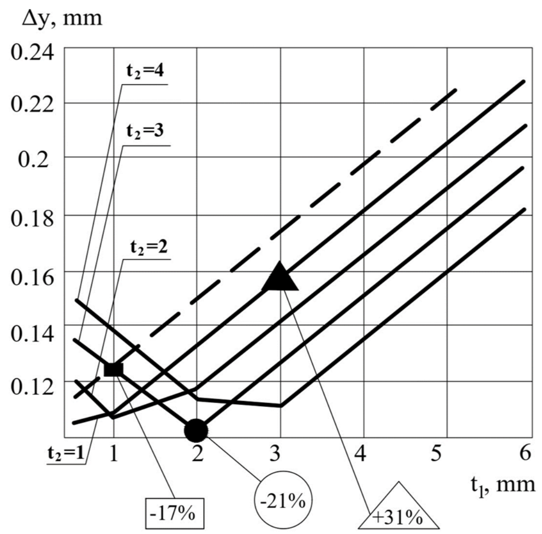
A number of variants (for example, basic, *d*) show that multi-tool two-carriage machining can give an error less than a single tool (in variant (*d*) by 21%.). The established operability of the model (5) and the coverage of factors taken into account allows using them as a basis for a control model for multi-tool two-carriage machining.



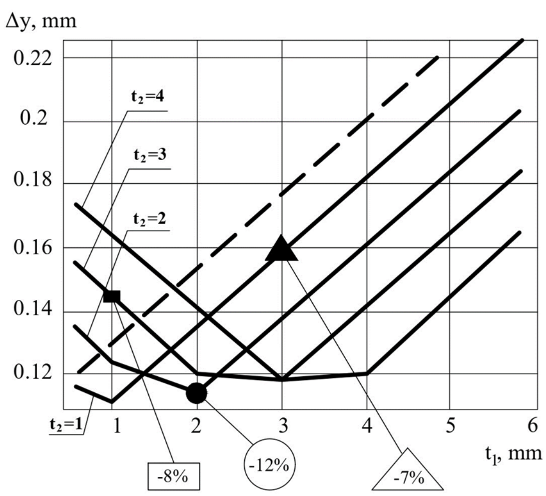
(a)



(b)



(c)



(d)

Figure 4. Influence of technological factors on the extent of the scattering area for diametrical sizes, performed by a longitudinal carriage in multi-tool double-carriage machining, (a) base variant, (b) ITZ_1 13, ITZ_2 13, (c) S_2 = 0.2 mm/rev, (d) r_1 = 1 mm, r_2 = 1 mm

Base variant:

(Adjustment $Y_0C_1^0(y)S_1(x)[u_1(y)]\cup Y_0C_2^1(y)S_2(y)[u_9(-y)]$ [1])

Workpiece: Steel 45, accuracy on $ITZ_1 12$, $ITZ_2 12$.

Longitudinal carriage: turning tool, $P6M5, j_1 = 60°, \gamma_1 = 15°, r_1 = 2$ mm, $S_1 = 0.3$ mm/rev.

Transversal carriage: facing tool, $P6M5, j_2 = 60°, \gamma_2 = 15°, r_2 = 2$ mm, $S_2 = 0.3$ mm/rev.

Instability of the technological system $\omega = 0.2$. Changes are indicated for other variants. The dashed line is the work of only the longitudinal carriage.

5. CONCLUSIONS

1. Matrix models are formulated to describe machining errors in multi-tool adjustments where the tools are arranged spatially. These models take into consideration the combined effects of all components of cutting forces from every adjustment tool and elastic deformations of the technological system in all spatial directions. These models are developed for both dimension distortion and scattering field representations.
2. Two limiting cases of multi-tool adjustments are given: opposite and non-opposite. The concept of homogeneous adjustments is introduced, the possibility of obtaining analytical models of scattering fields for them is explained, the formulas show the components of the matrix and vectors.
3. To clarify the differences in the mechanisms of formation of scattering fields, several definitions are introduced, both for the main and for the additional carriage. The analysis reveals that the scattering field is formed through the same mechanism in adjustments that are homogenous in the direction of cutting forces. However, for adjustments that are inhomogeneous in direction, there is no universal approach for computing scattering fields. Instead, the methodology for computing the scattering field needs to be developed independently for each direction.
4. The accuracy model developed for multi-tool adjustments enabled the evaluation of the extent to which various technological factors impact machining accuracy. These factors include the configuration of the multi-tool adjustment, the deformation characteristics of technological system subsystems, and cutting conditions.

REFERENCES

[1] N.D. Yusubov, "Multi-Tool Machining on Automatic Machines of the Turning Group (Matrix Theory of Accuracy of Multi-Tool Machining on Modern CNC Machines of the Turning Group)", AV Akademikerverlag Gmbh and Co. KG, LAP Lambert Academic Publishing, p. 256, Saarbrucken, Germany, 2013.
[2] N.D. Yusubov, "Fundamentals of Matrix Theory of Accuracy of Multi-Tool Turning, (Principles and Structure of the Theory) Design and Management of Multi-Tool Machining Processes", Omni-Scriptum GmbH and Co. KG / LAP LAMBERT Academic Publishing, 216 p, Saarbrucken, Germany, 2013.
[3] T.H. Dostalizade, R.N. Mehdizadeh, A.V. Bannikova, E.T. Abdullayev, "Engineering Design Problems", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 18, Vol. 6, No. 1, pp. 183-186, March 2014.
[4] M. Reuber, "CNC Multi-Spindle Automatic Lathes. Designs, Technologies, Use in Series Production", Springer Vieweg, p. 238, Wiesbaden, Germany, 2020.
[5] N. Yusubov, H. Abbasova, I. Khankishiyev, "Development of a Project Planning Theory for Multi-Tool Machining with the Possibilities of Modern CNC Machine Tools", Research in Engineering, Vol. 85, pp. 661-678, 2021.
[6] S.A. Bogatenkov, N.S. Sazonova, V.I. Guzeev, N.D. Yusubov, G.M. Abbasova, "Increasing the Productivity of Multitool Machining on Automated Lathes by Optimizing the Tool Positions", Russian Engineering Research, Vol. 41, pp. 1075-1079, 2021.
[7] S.A. Bogatenkov, N.S. Sazonova, N.D. Yusubov, P.V. Mammadov, R.I. Bazhenov, "Increasing the Productivity of Multitool Machining on Automated Lathes by Optimizing the Machining Plan", Russian Engineering Research, Vol. 41, pp. 1071-1074, 2021.

[8] S.A. Bogatenkov, N.S. Sazonova, N.D. Yusubov, H.M. Abbasova, B.B. Badalova, R.I. Bazhenov, "Decision-Making in the Conditions of Introduction of Automated Design Systems of Technological Processes", Socar Proceedings, Special Issue 1, pp. 006-010, 2022.
[9] A.A. Allahverdiev, "Automatic Method of Indexes Recording of Carriage Rolling Stock", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 7, Vol. 3, No. 2, pp. 114-118, June 2011.

BIOGRAPHIES

Name: **Nizami**
Middle Name: **Damir**
Surname: **Yusubov**
Birthday: 02.02.1965
Birth Place: Lankaran, Azerbaijan
Master: Machine-Building Technology, Metal-Cutting Machines and Tools, Azerbaijan Polytechnic Institute, Baku, Azerbaijan, 1989
Doctorate: Ph.D., Machine-Building Technology, Optimization of Surface Machining Plans in Lathe-Revolver Machines according to Productivity Criteria, Chelyabinsk Technical University, Chelyabinsk, Russia, 1993
Doctorate: D.T.S., Mechanical Engineering Technology, Increasing the Efficiency of Multi-Tool Machining in the Automatic Lathe-Machine Tool Group, Azerbaijan Technical University, Baku, Azerbaijan, 2011
The Last Scientific Position: Prof., Department of Machine Building Technology, Faculty of Machine Building and robotics, Azerbaijan Technical University, Baku, Azerbaijan, 2015
Research Interests: Designing Multi-Tool Machining, Mathematical Modeling and Optimization of Operations, Designing Surface Machining Plans
Scientific Publications: 184 Papers, 29 Books, 4 Patents, 4 Projects, 83 Theses

Name: **Isag**
Middle Name: **Abuzar**
Surname: **Khankishiyev**
Birthday: 30.01.1984
Birth Place: Lankaran, Azerbaijan
Bachelor: Shipbuilding and Ship Repair, Azerbaijan State Maritime Academy, Baku, Azerbaijan, 2005
Master: Shipbuilding and Marine Engineering, Azerbaijan State Maritime Academy, Baku, Azerbaijan, 2009
Doctorate: Shipbuilding and Ship Repair Technology, Azerbaijan State Maritime Academy, Baku, Azerbaijan, 2017
The Last Scientific Position: Assoc. Prof., Azerbaijan State Maritime Academy, Baku, Azerbaijan, Since 2021
Research Interests: Improvement of the Structural Strength of Ships, Safety, Sailing Qualities, Efficiency of Production and Repair Technologies
Scientific Publications: 32 Papers, 4 Books, 6 Textbook, 9 Teaching Aids, 12 Theses

Name: **Heyran**
Middle Name: **Murshud**
Surname: **Abbasova**
Birthday: 04.03.1987
Birth Place: Hajigabul, Azerbaijan
Bachelor: Renovation of Means of Production, Department of Machine Building Technology, Faculty of Machine Building, Azerbaijan Technical University, Baku, Azerbaijan, 2008
Master: Renovation of Means of Production (Engineering), Department of Machine Building Technology, Faculty of Machine Building, Azerbaijan Technical University, Baku, Azerbaijan, 2010
Doctorate: Machine Building Technology, Department of Machine Building Technology, Faculty of Machine Building and Robotics, Azerbaijan Technical University, Baku, Azerbaijan, 2021
The Last Scientific Position: Assoc. Prof., Department of Machine Building Technology, Faculty of Machine Building and robotics, Azerbaijan Technical University, Baku, Azerbaijan, 2021
Research Interests: Designing Multi-Tool Machining, Mathematical Modeling and Optimization of Operations, Designing Surface Machining Plans
Scientific Publications: 50 Papers, 2 Books, 1 Project, 2 Theses

Name: **Elkhan**
Middle Name: **Damir**
Surname: **Mammadov**
Birthday: 30.11.1984
Birth Place: Sumgait, Azerbaijan
Bachelor: Shipbuilding and Ship Repair, Azerbaijan State Maritime Academy, Baku, Azerbaijan, 2005
Master: Shipbuilding and Marine Engineering, Azerbaijan State Maritime Academy, Baku, Azerbaijan, 2007
Doctorate: Shipbuilding and Ship Repair Technology, Azerbaijan State Maritime Acad., Baku, Azerbaijan, 2016
The Last Scientific Position: Assoc. Prof., Azerbaijan State Maritime Academy, Baku, Azerbaijan, 2021
Research Interests: Improvement of the Structural Strength of Ships, Safety, Sailing Qualities, Efficiency of Production and Repair Technologies
Scientific Publications: 31 Papers, 2 Books, 3 Textbook, 9 Teaching Aids, 11 Theses

Name: **Rasul**
Middle Name: **Arastun**
Surname: **Huseynov**
Birthday: 22.10.1966
Birth Place: Jalilabad, Azerbaijan
Master: Mechanical Engineer, Marine Eng. Univ., Odessa, Ukraine, 1992
Doctorate: Student, Azerbaijan State Maritime Academy, Baku, Azerbaijan, Since 2022
The Last Scientific Position: Assist. Researcher, Azerbaijan State Maritime Academy, Baku, Azerbaijan, Since 2020
Research Interests: Improvement of Structural Strength of Ships, Safety, Sailing Qualities, Efficiency of Production and Repair Technologies
Scientific Publications: 4 Papers, 3 Theses