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machining, turning,
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ADAPTIVE HEAD FOR AUTOMATIC COMPENSATION OF ELASTIC DEFORMATIONS IN THE MACHINING SYSTEM AFFECTING TURNING ACCURACY

This paper presents a new adaptive head (catridge) solution, developed based on patent PL 245622, that automatically compensates for elastic deformations of the entire MFWT (Machine tool, fixture, workpiece, cutting tool) system. This enables improved machining accuracy and turning efficiency. The principle of operation of the cartridge is described, as well as the possibilities of adapting its settings to the conditions in which it is expected to operate effectively. A theoretical and experimental analysis of the effectiveness of this cutting process support is presented.

1. INTRODUCTION

Since the beginnings of metal cutting, efforts have been made to increase machining efficiency while maintaining or improving accuracy. Establishing machining conditions that reduce turning errors makes it possible to reduce the number of passes and/or increase cutting parameters. One of the main causes of turning errors is the elastic compliance of the machining system [1].

The aim of this paper is to present the possibility of automatically compensating for turning errors caused by the compliance of the machining system (MFWT) using a simple mechanical cartridge that does not require numerical control. This paper continues the previous studies reported in Refs. [2, 3, 4].

Factors related to the cartridge design that significantly affect its accuracy and effectiveness are presented.

2. FACTORS AFFECTING TURNING ERRORS

Several dozen factors affect turning errors. They are most often discussed in terms of machine-tool geometry and kinematics, tool condition, workpiece stiffness and clamping,

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process parameters, workpiece material, and human error. These factors are widely known and will not be discussed in detail here [5]. Some act in a repeatable manner and are relatively easy to correct, others are stochastic, making them much more difficult and not always possible to eliminate completely.

The elastic compliance of the components of the machining system (MFWT) has a significant effect on the geometrical accuracy of the workpiece, as well as on vibration characteristics and cutting-process stability. Cutting forces deform the system components, causing displacement of the tool relative to the workpiece. This leads to errors in dimensions and forms whose magnitude depends, among other things, on system stiffness and variations in load during machining. Therefore, reducing the effect of system compliance on the cutting process is important for improving machining accuracy.

The compliance of the machine system (MFWT) is the primary cause of the phenomenon known as the "replication of workpiece blank errors." More specifically, this relates to the impact of a variable machining allowance, which encompasses both the initial errors in the workpiece blank and any asymmetry in how the workpiece is clamped on the lathe. The greater the local machining allowance, the higher the cutting forces. These lead to increased elastic deformation within the MFWT system, ultimately resulting in greater machining errors.

To a greater or lesser extent, this effect occurs in almost all metal-cutting processes. It becomes more pronounced when:

- the entire MFWT system is more susceptible to elastic deformation,
- the machining allowance is distributed less uniformly,
- cutting resistance is higher. Cutting resistance depends on the hardness and strength of the workpiece material, cutting parameters, cutting-edge geometry and rake-face features (chip breakers and chip formers), lubrication and cooling of the cutting zone, tool-edge coatings, the selected tool-wear criterion, etc.

Workpiece error copying necessitates several machining passes or a reduction in feed so that the effect diminishes with each successive tool pass until the required accuracy is achieved. This reduces productivity and cutting efficiency.

3. METHODS FOR REDUCING TURNING ERRORS CAUSED BY MACHINING-SYSTEM COMPLIANCE

There are many causes of workpiece error copying and, accordingly, many ways to reduce its effects. The most common methods include:

- Selecting appropriate cutting conditions by reducing feed rate s and depth of cut ap, or using other methods to reduce cutting resistance.
- Symmetrical clamping of the workpiece on the machine-tool spindle axis.
- Using more accurately manufactured blanks with smaller machining allowances.
- Using special sizing tools, such as reamers, including tools for external surfaces, that are insensitive to elastic deformation.
- The trial-pass method: after machining the first workpiece (or, for large workpieces, only the surfaces with the most stringent requirements) measure the workpiece and

apply suitable corrections to the tool movements at locations where dimensions fall outside the tolerance range. These adjustments can be made manually or automatically in the NC program [6].

- Methods for online automatic compensation of elastic deformations in the MFWT system.

The latter methods are usually implemented using mechatronic or mechanical tools, such as special cartridges.

To reduce errors caused by elastic deformation of the MFWT system, work continues on the development of new error compensation methods. These efforts address the following aspects: structural optimization to achieve the required stiffness [7], optimization of machining parameters and strategies [8] and clamping conditions [9], and compensation for predicted or indirectly measured deflection using error functions [2]. Most recent research focuses on deflection compensation using geometric-control algorithms (G-code and macros [10]) or error prediction [11]. Work is also ongoing to ensure adequate measurement accuracy and to select suitable methods for measuring stiffness and cutting forces. Measurement uncertainty is particularly important when measuring MFWT systems with low or medium stiffness [12]. For highly rigid systems, where deformations are small but still significant, research is being conducted into microscale measurement methods, for example, to determine roughness-induced deformation between two contacting flat surfaces [3]. Precise measurements and contact-characteristic data can improve the determination of MFWT stiffness and help increase mechanical-system stability so that machining tolerances can be met.

Recent literature contains more design solutions for mechatronic tools that compensate for elastic deformation in the MFWT system than for mechanical solutions. Research is dominated by mechatronic systems, which are mainly used in nanotechnology with Fast Tool Servo (FTS) systems [13]. In contrast, mechanical solutions operate over a larger displacement range and do not require expensive control systems. Their main common feature is that they can be used on conventional machine tools.

Potential advantages of mechatronic tools designed to compensate for elastic deformation include:

- the ability to operate automatically,
- the ability to reduce vibration, particularly when using low-stiffness tools with large overhangs, such as boring bars, which can also increase machining productivity,
- high versatility, allowing internal and external surfaces to be machined in kinematic systems where either the workpiece or the tool rotates [14],
- the ability to be used on machine tools of relatively simple design that do not need NC systems, because the tools can use their own independent control system [4],
- the ability to correct deviations of the cutting-edge corner from its intended path, whether the path is straight or curved and whether motion is controlled manually, mechanically, or by a program.

In many older designs, mechatronic tools correct or minimize elastic deformation of the tool alone, disregarding deformation of the other components of the machining system. However, this approach has changed in recent years, and the importance of all MFWT

components, not just the tool itself, has repeatedly been emphasized. This shift can be seen in research on both turning and milling [15].

4. OPERATING PRINCIPLE OF THE CARTRIDGE FOR COMPENSATING FOR ELASTIC DEFORMATION OF THE MACHINING SYSTEM

The cartridge mechanism is shown schematically in Fig. 1. It accounts for and compensates for elastic deformation of all MFWT components that affect the radial displacement of the tool tip from its intended path. The cartridge has a simple design and is intuitive to operate. Its operation is based on the principle described in patent PL 245622 [16].

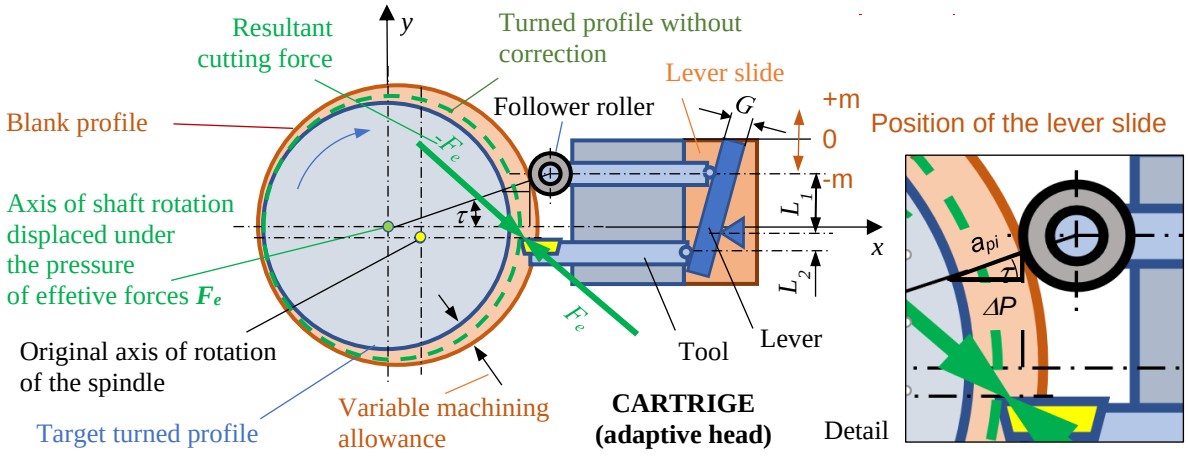


Fig. 1. Operating principle of the correction cartridge designed to compensate for elastic deformations in an MFWT system (according to patent PL 245622); F_e – effective force, G – thickness of the lever, L_1, L_2 – distance from the lever's rotation, m – position of the lever's slide, ΔP – displacement of the roller at an angle τ relative to the allowance a_{pi}

The cartridge operates as follows. The follower roller is pressed against the machined surface by cutting forces transmitted through a lever. The contact force exerted by the roller is proportionally lower than the cutting force and depends on the ratio $p = L_2/L_1$. The roller travels along the surface just ahead of the cutting tool. A varying machining allowance (a_{pi}) displaces the roller, causing the lever inside the cartridge to pivot. The lever has an adjustable ratio p and moves the tool along the x-axis in the direction opposite to the elastic deformation of the MFWT system. The ratio depends on the stiffness of the MFWT system and is adjusted by moving the lever pivot within the lever slide in which the lever is mounted ($\pm m$). The greater the system compliance in the x-direction, the greater the lever ratio should be.

During turning without compensation, elastic deformations can cause the shape and dimensions of the workpiece to deviate from the intended specifications. This is illustrated by the green dashed line in Fig. 1. When compensation is applied, the tool is shifted by an amount that allows the tool's cutting edge to turn the intended diameter after the system has deformed.

The proposed correction system, in the form of a mechanical cartridge, has the advantage that it can operate automatically without using the machine tool's numerical control.

5. SIMULATION OF CARTRIDGE OPERATION AND ANALYSIS OF ITS COMPENSATION CAPABILITIES

The formation of the elastic-deformation components in the MFWT system is illustrated in Fig. 2. It is assumed that the resultant force $\vec{F_e}$ from the cutting forces and the roller's contact force on the workpiece deforms the system by ΔMFW towards the workpiece, while the reaction $-\vec{F_e}$ causes the tool to move in the opposite direction by ΔT. As a result, the instantaneous workpiece radius Ri, according to Pythagoras' theorem and the diagram in Fig. 2, is given by (1).

$$R_{(i)} = \sqrt{\left(\Delta W_y + \Delta T_y\right)^2 + (\Delta W_x + R_1 + \Delta T_x)^2} \tag{1}$$

As the shaft rotates, the following quantities vary instantaneously, usually periodically, and interact in sequence: machining allowance (depth of cut) → cutting forces → elastic deformation of the machining system → change in the workpiece radius. A theoretical analysis of the cartridge therefore requires the following to be determined in this order:

1. The varying machining allowance a_{pi} around the workpiece circumference.
2. The relationship between cutting forces and depth of cut, $F_e = f(a_{pi})$.
3. The stiffness of the MFWT system in the directions of the workpiece (ΔMFW) and the tool (ΔT).
4. Set the cartridge lever ratio by changing the position m of the lever slide (Fig. 1).

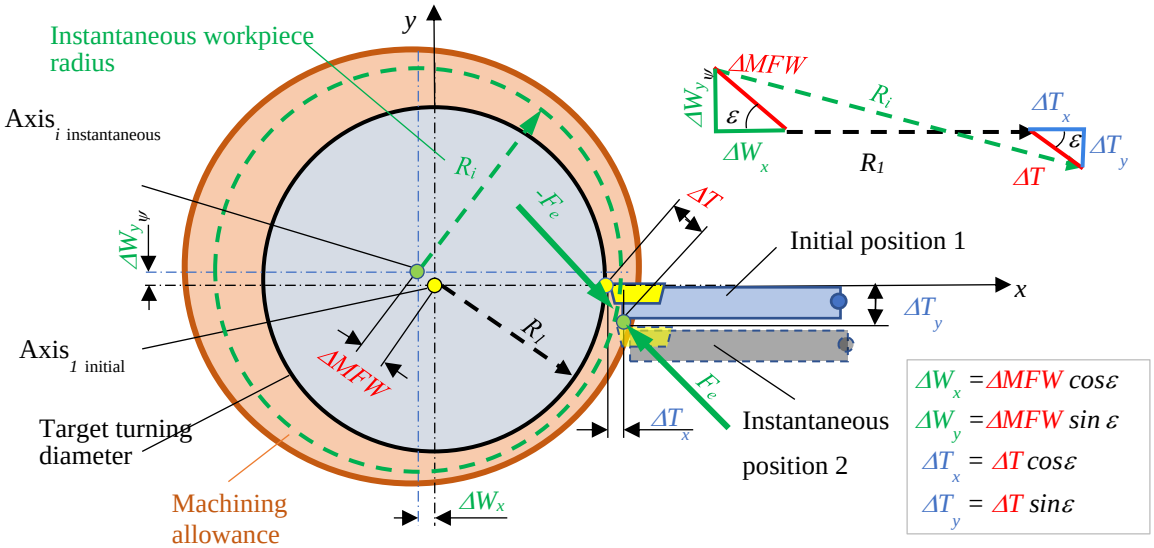


Fig. 2. Mechanism of the formation of strain components in the MFWT system; ΔMFW (ΔW_x, ΔW_y) - change in the position of the workpiece axis of rotation; ΔT (ΔT_x, ΔT_y) - the cutting tool; $R_{1...i}$ - instantaneous workpiece radius; F_e - effective force acting at an angle ε

The procedure described above is illustrated graphically in Fig. 3 for an example value of a_{pi} = 0.6 mm. The successive steps are numbered 1,2,…8.

The instantaneous turning radius R_i must take into account the following effects during cutting:

- the workpiece centre of rotation is displaced by ΔMFW,
- the tool tip retracts by ΔT,
- the values of ΔMFW and ΔT depend on the magnitudes and directions of the forces $\vec{F_e}$, $-\vec{F_e}$ and their components, which in turn depend on the instantaneous machining allowance a_{pi}.

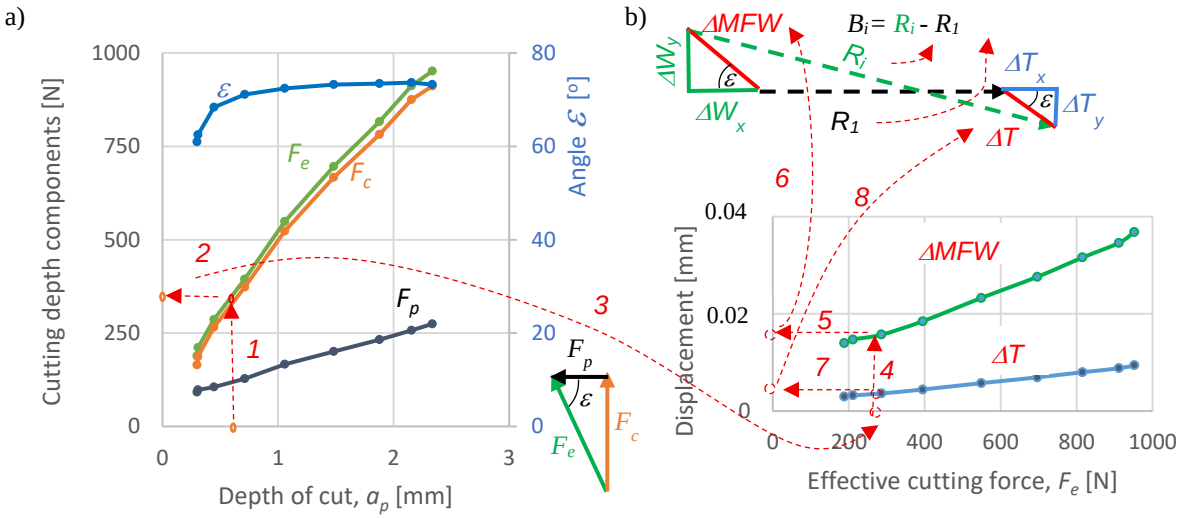


Fig. 3. Methodology and procedure for determining the instantaneous workpiece radius R_i for an example depth of cut a_p = 0.8 mm: a) Cutting depth components F_e (the effective cutting force), F_c,(the cutting force), F_p (the radial force), and angle ε versus depth of cut a_p [N]; b) Change in the position of the workpiece axis of rotation (ΔMFW) and the cutting tool (ΔT) as a function of the effective force (F_e); $B_i = R_i - R_1$ – instantaneous radial error

Following this procedure and using the assumed theoretical conditions, a sample radar chart was prepared (Fig. 4) to compare the distribution of machining allowance around the workpiece circumference with radial errors of the workpiece, both with and without the cartridge. The radial error after turning with the cartridge ($B_{i\text{-}estim}$) was estimated theoretically according to the procedure shown in Fig. 3. Machining allowance a_{pi} and the radial error B_i (after cutting without the cartridge) are determined for 16 points on the workpiece.

The figure shows that the radial turning error is almost completely compensated for at the maximum machining allowance. At other locations, particularly where the allowance is smallest, compensation is less complete.

As a result, the maximum radial error should be reduced from approximately 0.06 to 0.01 mm. The reasons for the incomplete compensation of this are:

- the effect of lever thickness G on the nonlinearity of the cartridge lever ratio (for $G = 0$, the ratio is linear; see Fig. 5),
- the lead angle τ between the follower roller's position and the cutting point (Fig. 1),
- the roller displacement ΔP as a function of angle τ is given by $\Delta P = a_{pi} \cos\tau$ (Fig. 1). This displacement is smaller than the allowance a_{pi}, so the lever pivots less than required and the tool retraction ΔT is smaller than necessary. The resulting disturbance increases as angle τ increases.

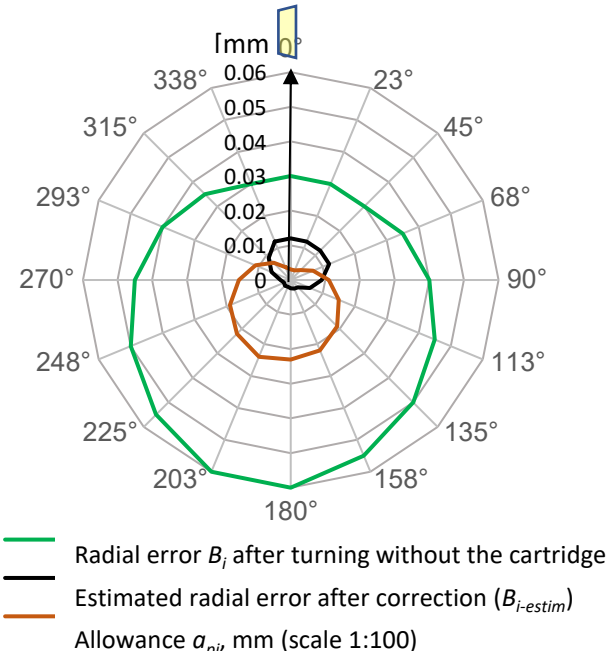


Fig. 4. An estimated comparison of the distribution around the shaft circumference of the machining allowance and the radial errors from the intended geometric shape of the machined surface, with and without the use of the cartridge

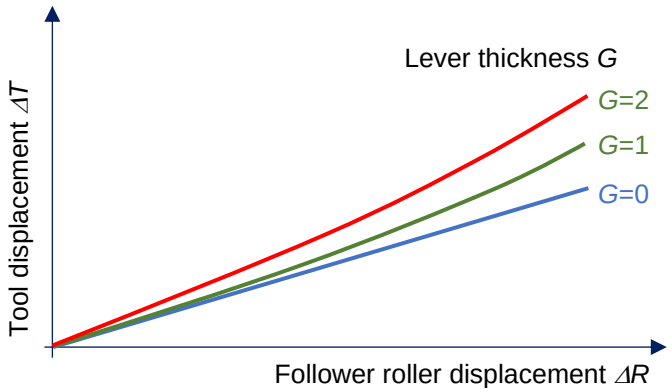


Fig. 5. Dependence of the lever ratio on its thickness G in the adaptive head (cartridge)

Determining the cartridge setting m for specified machining conditions to achieve correct compensation requires the following steps:

1. Determine the instantaneous radial errors $B_i = R_i - R_1$ (Fig. 2) that would occur without any correction to the tool position. This should be done for successive angular positions i of the shaft.
2. The local turning error B_i is the amount by which the tool position must be corrected to obtain the desired dimension and machined-surface shape.
3. Next, determine the cartridge lever ratio p. As the current cartridge design does not allow the lever ratio to be adjusted online, it must be set for the maximum error value, $B_{i\,max}$ using Eq. (2).

$$p = \frac{B_{i\,max}}{a_{pi\,max}} \tag{2}$$

   For smaller turning errors, the correction may not fully compensate for the machining errors (Fig. 4).
4. The position m of the cartridge lever slide can be determined from the cartridge characteristic curve $m=f(p)$ (Fig. 6).

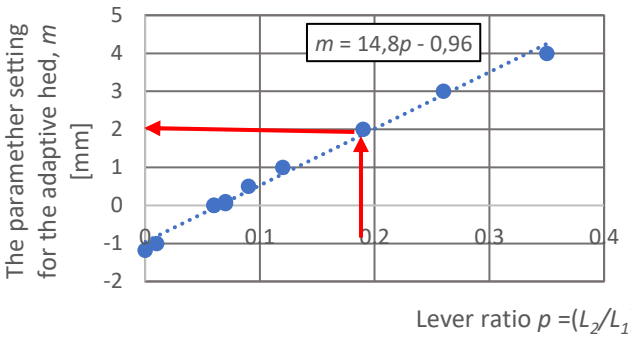


Fig. 6. Dependence of the m parameter setting for the adaptive head on the lever ratio p

A complete experimental investigation and analytical verification are difficult because many factors change simultaneously during cutting (Fig. 7), including:

- the non-uniform machining allowance around the shaft circumference and along its axis,
- variation in MFWT system compliance along the shaft axis,
- the highly dynamic phenomena associated with high workpiece rotational speeds and the time delay caused by the response of the correction mechanisms,
- non-linearity of the lever ratio p in the adaptive head,
- the instantaneous machining allowance is determined with advanced by an angle τ.

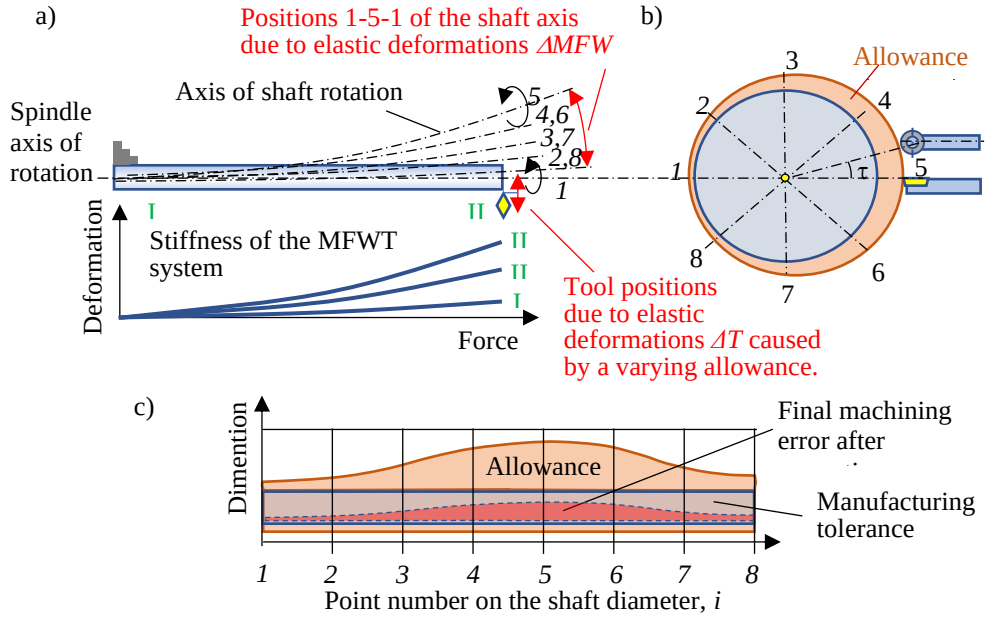


Fig. 7. Complexity of phenomena occurring during machining; a) elastic deformation of the MFWT system; b) points on the shaft diameter corresponding to machining allowances; c) final machining error in relation to manufacturing tolerances and allowance

6. CONCLUSIONS

Effective methods are available for automatically assisting the cutting process by compensating for elastic deformation of the MFWT system. This makes it possible to:

- improve machining accuracy,
- reduce the number of machining passes,
- increase cutting parameters,
- shorten machining time and improve cutting efficiency.

The methods presented can be implemented using mechatronic tools or much simpler mechanical systems, such as the cartridge described in this paper. In the context of analytical research, the use of the presented cartridge makes it possible to reduce the maximum radial error from ~0.06 mm to ~0.01 mm.

Further analytical research, including modifications to the cartridge design and experimental verification of its operation, will be presented in a subsequent publication.

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