Improvement of NC Program Quality based on Shape Generation Motions and Feed Drives for Five-Axis CNC Machine Tools

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ABSTRACT

Five-axis Computer Numerical Control (CNC) machine tools, integrated with Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) systems, are used to machine complex parts and reduce trials and errors. However, these machine tools still rely on Numerical Control (NC) programs and often lack accuracy and precision due to poor quality when implemented in the machine. This research aims to enhance the quality of NC programs for five-axis CNC machine tools by focusing on shape generation motions and a closed-loop feed drive system with Proportional-Integral-Derivative (PID) control. The individual motions were mathematically described using 4x4 transformation matrices, incorporating kinematic motion deviations, end mill geometry, machining parameters, and cutting forces derived from virtual machining. Additionally, a closed-loop feed drive system with PID control was integrated with the new position and angular data of each axis from the shape generation motions model. The new NC programs were validated by machining an S-shaped part and measuring dimensional errors at 64 points before and after using a Coordinate Measuring Machine (CMM). The results indicate a substantial reduction in the standard deviations of form and angular errors within the NC program quality, totaling approximately 80.73%. Reductions are demonstrated in the standard deviations for the X, Y, A, and B axes, with decreases of 76.83%, 95%, 82.40%, and 68.72%, respectively indicating a significant improvement in the overall quality of the NC program.

Keywords-computer aided design; computer aided manufacturing; shape generation motion; computer numerical control machine tools; machining; feed drives

I. INTRODUCTION

In recent years, manufacturing processes have actively pursued developments to enhance product quality and decrease production expenses. In particular, machine tools have continuously investigated innovative methods to accomplish these aims. The incorporation of cutting-edge digital engineering technologies has emerged as a fundamental component of contemporary machining procedures.

CAD, Computer-Aided Engineering (CAE), and CAM systems are now widely used for the design, analysis, and production of mechanical products. These technologies enable more precise control over the manufacturing of complex parts. Notably, five-axis CNC machine tools have become a key solution for machining free-form surfaces, as they offer the capability to precisely control both the position and orientation of cutting tools relative to the workpiece. This level of precision has made five-axis CNC machining a critical element in modern manufacturing processes [1, 2]. Although additive manufacturing techniques have been introduced as an alternative for creating complex geometries, they often fall short in meeting the necessary standards for mechanical properties and surface finish, limiting their application in certain areas. Consequently, five-axis CNC machining remains a highly suitable method for producing mechanical parts that require high precision and superior surface quality [3].

However, five-axis CNC machines are generally prone to higher geometric and kinematic errors compared to three-axis machines, due to the increased complexity of managing three translational and two rotational axes. These deviations complicate the ability to meet stringent precision standards in high-accuracy manufacturing. Frequent adjustments, iterative testing, and time-intensive processes are often necessary to ensure the desired level of precision. Consequently, a thorough investigation of the error sources in five-axis machines, coupled with a focus on enhancing NC program quality before machining, is crucial. Among the various error sources, geometric and kinematic deviations representing quasi-static errors between the cutting tool and the workpiece present the greatest challenge, significantly impacting machining accuracy and overall performance [4-8].

This transformation has been facilitated by the development of Virtual Machining Systems (VMS), which are designed to digitally replicate real-world manufacturing processes before actual production conserving time and resources. VMS provide a virtual platform to simulate machining operations, enabling the generation of optimized NC codes that enhance efficiency and precision in actual production [9, 10]. As an advanced simulation methodology, VMS are highly effective in predicting and controlling various machining parameters, such as three-dimensional tolerances and surface roughness. This is achieved by incorporating kinematic motion deviations, tool wear, and workpiece deflection into the model, allowing for a more accurate representation of the actual machining process.

Recent research proposed models to predict contouring errors caused by cutting forces in virtual CAM environments. These models aim to improve CNC accuracy by developing mathematical representations of kinematic deviations, enabling better control over the final output [11-17]. Furthermore, virtual machining models have been extended to address dimensional, geometrical, and tool deflection errors in CNC machining centers. These systems generate improved NC codes that accurately simulate machining processes in a virtual environment, enhancing both precision and operational efficiency. Improving the accuracy of cutting force coefficients allows for more efficient and precise calculations in real-world machining [18-22].

Despite the advancements in VMS, there remain challenges to be addressed, particularly in optimizing workpiece accuracy and refining production processes using these digital systems. While current research has primarily focused on VMS under ideal cutting conditions utilizing CAD/CAM, further studies are needed to investigate how virtual machining can enhance the quality of NC programs by accounting for deviations in shape generation motion, especially in five-axis CNC machines. Incorporating considerations of kinematic motion variations in NC programs is crucial for achieving higher machining precision. Several researchers have proposed methods to optimize NC program quality by incorporating factors, such as kinematic deviations, geometrical inaccuracies, and tool deflection.

Even though extensive research has been conducted on the application of virtual machining to real-world manufacturing environments, there is still significant potential for further exploration in this field [14, 23-24]. High-quality surface finish has become a critical performance metric in modern manufacturing, particularly in the context of high-speed CNC machining. The existing body of research on enhancing the quality of NC code based on shape generation motion deviations in virtual machining for five-axis CNC machines is limited. Consequently, there is a substantial opportunity for future research to delve deeper into these areas and develop novel strategies to enhance the precision and efficiency of high-speed manufacturing processes [25-27]. The proposed method represents a significant advancement in the field of CNC machine tool operations by optimizing the NC program for five-axis CNC machining. This approach offers a more accurate representation of the real-world milling process, leading to enhanced control over tool motion and improved compliance with design specifications. As a result, this technique contributes to enhancements in both manufacturing efficiency and product quality, reducing the need for post-machining corrections and adjustments. By ensuring a more precise NC program, manufacturers can achieve higher productivity, reduced material waste, and superior surface quality in the final product.

II. EXPERIMENTAL PROCEDURE

A. *Framework of NC Program Quality Based on Shape Generation Motions and Feed Drives*

Five-axis machine tools enable precise control over both tool orientation and position in relation to the workpiece, commonly used for shaping complex geometries in aerospace systems and components, such as impellers. Despite their advantages, these machines face operational challenges, particularly lower motion accuracy, compared to their conventional three-axis counterparts, due to inherent error sources. Consequently, multiple researchers have investigated methods to enhance the NC Program quality of five-axis CNC machine tools.

The present study uses a simulation methodology, as illustrated in Figure 1, starting with experimental machining and precise measurements, followed by iterative adjustments to axis positions and angles through virtual simulation and closed-loop control. Position and angular refinement is facilitated using simulation software like Simulink, and the S-shaped component can be simulated utilizing tools like Fusion 360.

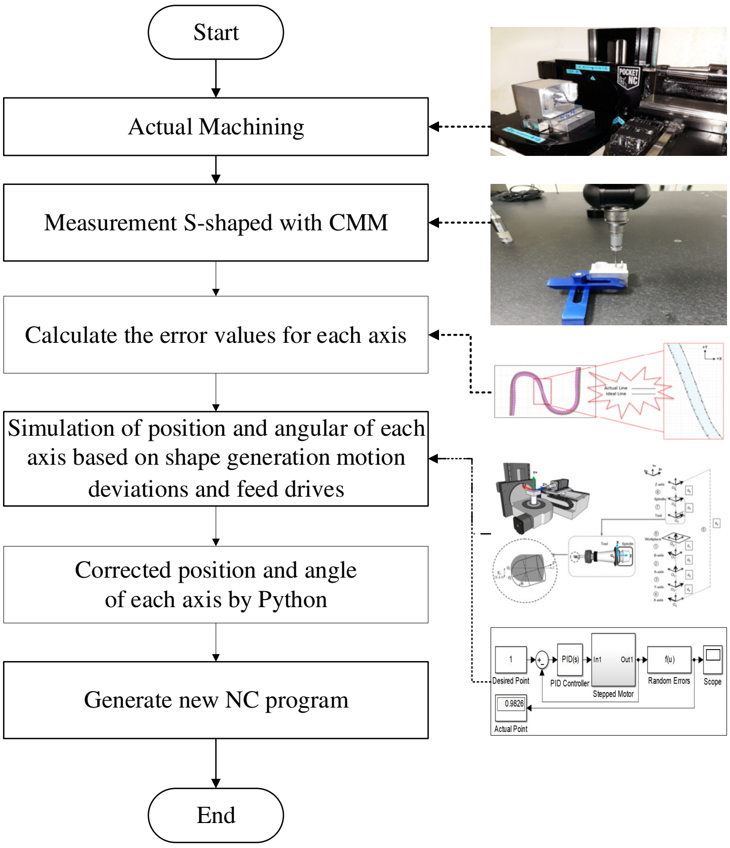


Fig. 1. Framework of NC program quality based on shape generation motions and feed drives.

B. *Shape Generation Motions*

1) *Diagram of Shape Generation Motions*

The precision of machined product dimensions and surfaces is crucial, and understanding the complex relationships involved often relies on simulating the inherent shape generation processes of machine tools. Geometric imperfections on product surfaces commonly arise from various sources, such as errors in the interaction between cutting tool inserts and workpieces, which significantly impact tool wear, surface finish, and overall machining efficiency. By comprehending these interactions, it is possible to optimize cutting conditions, extend tool lifespan, and enhance the quality of machined components. Additionally, inherent tolerances and irregularities encountered during material removal further complicate these processes, potentially leading to geometric inaccuracies in the final product. The relationships among these factors remain an area requiring further research [8, 10]. Consequently, this research focuses primarily on exploring the kinematic motion deviations occurring during the relative movements between cutting tool inserts and workpieces. The shape generation processes are typically explained by illustrating the shape generation motions and the geometries of the cutting tool inserts. These movements describe the relative motions of cutting tool inserts in relation to workpieces, performed by a series of rigid components integral to the machine tools, through a model of shape generation motions that provides a comprehensive analysis of machining errors within these movements [28-30]. The model utilizes a chain-link diagram representing the shape generation process, where S_0 denotes the workpiece, S_l signifies the cutting tool inserts, and S_1 through S_l serve as intermediate links, with the motion parameters of the units represented by q_1, q_2, ..., q_l, and the corresponding relative motions denoted by k_1, k_2, ..., k_l.

2) *Functions of Shape Generation Motions*

Considering the coordinate transformation between the two coordinate systems, S_{i-1} and S_i, reveals that a point in space generally possesses distinct coordinates in these systems, with the exception occurring only if S_{i-1} and S_i are identical. Let X_0 and X_l denote the position vectors of the point in each respective coordinate system. These vectors are related through:

$$X_0 = A_{ij}(q_1, q_2, \dots, q_l)X_l \tag{1}$$

X_l is the position vector of the cutting tool inserts, defined with respect to a point on the cutting edge in the tool coordinate system, X_0 *is* the position vector of the point, as specified in the workpiece coordinate system, and A_{ij} are the 4x4 coordinate transformation matrices depicting the relative positions and kinematic motions between two rigid bodies, denoted as *i* and *j*. Each matrix includes a 3x3 block in its upper left corner, which defines the rotational orientation of system S_i with respect to its coordinate origin O_i. This rotation ensures that the axes of both systems S_{i-1} and S_i are aligned in order for them to be parallel and similarly oriented.

Considering systems S_{i-1} and S_i, each representing consecutive links in shape generation, where the relative motions between them adhere to six fundamental constraints, the relationship between these motions can be represented by:

$$A_{ij}(q_1, q_2, \dots, q_l) = \prod_{i=1}^{l} A^{ai}(d_i) \tag{2}$$

$A^{ai}(d_i)$ refers to the 4x4 transformation matrices depicting deviations in kinematic and positional motions, where α_1 through a_i indices are used to denote the directions of kinematic motions and positions. In this context, (1-3) refer to linear motions and positions along the X, Y, and Z axes, respectively, while (4-6) indicate rotational motions and positions around the X, Y, and Z axes [29, 30]. Finally, d_i is the parameter indicating the relative positions of the axes.

The specified relative motions generally consist of either translational motions along the X, Y, and Z axes or rotational motions about the X, Y, and Z axes. To investigate the motion errors of machine tools, the kinematic model is formulated using Homogeneous Transformation Matrices (HTMs) to account for both translational and rotational errors. Each error type within this model is meticulously defined and analyzed using HTMs to determine its impact on the accuracy and precision of positioning the cutting edge for cutting tools relative to the workpiece. In the context of any linear motion, a rigid body encounters six error components, comprising three rotational deviations and three translational deviations. The HTMs are obtained by multiplying the transformation matrices of A_1, A_2, and A_3, as shown in (2). Similarly, the HTMs for the three rotations are obtained by multiplying the transformation matrices A_4, A_5, and A_6. The infinitesimal matrix $\mathbf{E}_{ij}$ represents the position errors of the i-th link. These six error parameters for linear movement are:

$$\mathbf{E}_{ij} = \begin{bmatrix} 1 & -\varepsilon_z & \varepsilon_y & \delta_x \\ \varepsilon_z & 1 & -\varepsilon_x & \delta_y \\ -\varepsilon_y & \varepsilon_x & 1 & \delta_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

where δ_x, δ_y, δ_z refer to positional errors along the X, Y, and Z axes and ε_x, ε_y, ε_z to angular errors around the X, Y, and Z axes.

Six parameters, derived from a normal distribution, are used to characterize kinematic motion deviations in virtual machining. Although the International Organization for Standardization 841 standardizes the terminology for machine motion axes, simply labeling these axes is insufficient to address machine geometric errors or enable effective compensation. This section outlines a systematic approach, in accordance with ISO 230-1 standards, for establishing a precise machine tool coordinate system to improve Numerical Control programming through virtual machining. Determining the accurate positions and orientations of these axes within a coordinate system facilitates the identification of alignment errors. This process is crucial for evaluating geometric accuracy and implementing software-driven error compensation strategies across diverse machine configurations. In this study, the proposed machine tool coordinate system is applied to the coordinate systems of a mini five-axis Computer Numerical Control milling machine used for milling operations.

3) Cutting Force Model of End Mills

The five-axis CNC milling process involves the interplay between cutting tools, inserts, and the workpiece, relying on their relative motion. This process entails applying cutting forces and generating machined waste. Three simulation models are proposed that classify cutting forces into three categories based on their manifestation during end milling with a ball-nose cutter [31]. These models define the end mill parameters as tangential force (F_T), radial force (F_R), and axial force (F_A), which act on the groove at the position of the cutting rotation angle (φ). The behavior of these forces can be analyzed using the Lumped Mechanism Model (LMM), calculated by (4) [32]:

$$\begin{aligned} F_{T,i,j}(\varphi) &= K_{Tc} h_{i,j}(\varphi) b_{i,j} + K_{Te} b_{i,j} \\ F_{R,i,j}(\varphi) &= K_{Rc} h_{i,j}(\varphi) b_{i,j} + K_{Re} b_{i,j} \\ F_{A,i,j}(\varphi) &= K_{Ac} h_{i,j}(\varphi) b_{i,j} + K_{Ae} b_{i,j} \end{aligned} \tag{4}$$

The functions $h_{i,j}(\varphi)$ and $k(z)$ denote the thicknesses of precut scrap at the cutting angle and the rotational angle of the end mills during cutting, relative to the axial element j-th of i-th grooves, respectively. The final component of the cutting forces, $F_s(\varphi)$ at the cutting rotation angle is determined by summing the forces acting on the tooth grooves and elements. To improve the accuracy of virtual cutting simulations, these calculations must be integrated with (2) into a single unified function:

$$h_{i,j}(\varphi) = h_{i,j}^{c}(\varphi) \sin k(z) \tag{5}$$

$$b_{i,j} = z_{i,j} / \sin k(z) \tag{6}$$

$$F_s(\varphi) = \sum_{i,j} F_{s,i,j}(\varphi), \text{where } s = \mathrm{X, Y \text{ or } Z} \tag{7}$$

where K_{Tc}, K_{Rc}, K_{Ac}, K_{Te}, K_{Re}, K_{Ae} depict the coefficients of cutting force corresponding to chip shearing and edge rubbing along the tangential, radial, and axial directions, respectively.

4) Shape Generation Motions of Five-Axis CNC Milling Machine

The five-axis CNC milling machines utilized in modern manufacturing exhibit significant diversity, with each of them possessing unique physical structures and components. This investigation employs a miniature five-axis horizontal milling machine from the Pocket NC Company, specifically the Model V2-10. This machine is equipped with three linear motions along the X, Y, and Z axes, as well as rotational motions along the A and B axes, which rotate around the X and Y axes, respectively. The coordinate systems are established in compliance with the ISO 230-1 standard. Consequently, eight Cartesian coordinate systems, as illustrated in Figure 2, are defined to represent the kinematic motion for the purpose of shape generation.

These coordinate systems, designated O_1 through O_7, correspond to the coordinate systems of the workpiece and the cutting edges, respectively, and are calculated using (8), where

r_w represents the position vector at the point of the workpiece coordinate system, while r_e denotes the position vector at the point on the cutting edge of end mill coordinate system. Additionally, E_{ST} refers to the deflection of the end mill due to the cutting force. The errors observed in mini five-axis CNC milling machine tools were systematically analyzed according to the guidelines of the ISO 10791-6 standard and in accordance with thirteen systematic deviations identified in a five-axis machining center [33]. Positional and rotational errors between each axis pair were determined using:

$$\begin{aligned} r_w = {} & A^2(d_1y)A^5(\gamma)E_{BA}A^1(d_2x)A^4(\alpha)E_{AY}A^2(d_2y) \\ & A^1(d_3x)A^2(d_3y)E_{YX}A^3(d_3z)A^3(d_4z)A^1(d_4x) \\ & A^2(d_4y)E_{XZ}A^3(d_5z)A^2(d_5y)A^3(d_6z) \\ & E_{ZS}A^6(\theta)E_{ST}r_e \end{aligned} \tag{8}$$

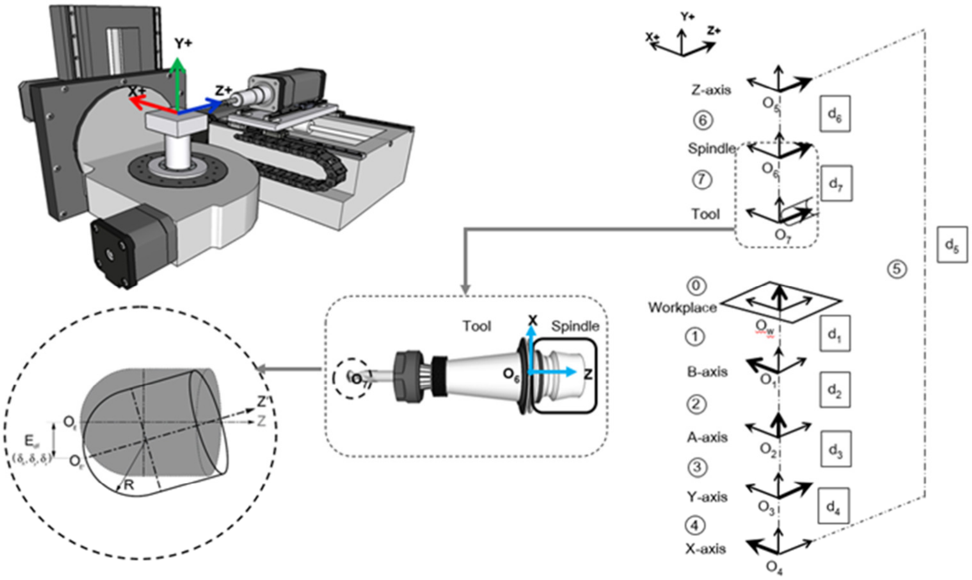


Fig. 2. Coordinate systems of the main motion of a mini five-axis CNC milling machine.

C. *S-Shaped Machining and Measurement*

1) *S-Shaped Machining*

ISO 10791-7 establishes a standardized framework for evaluating the machining performance of machine tools. Multi-axis machine tools are well-suited for testing the S-shaped workpiece, which is notable for its variable curvature, open-close angle conversion, and twist angle, making it particularly effective for assessing diverse sculpted surfaces [33, 34]. Accordingly, this study selects the S-shaped test piece as the machined workpiece, as its form error accurately reflects machining accuracy. The S-shaped configuration has been proposed for evaluating the performance of five-axis milling machines. It comprises four curves, each defined by sixteen control points [35]. These four curves are paired to form the shape: control curves P and M create the upper surface of the S-shape, while control curves Q and N form the lower surface. Utilizing CAD functions, the resulting S-shape is presented in Figure 3. Since the dimensions derived from the coordinate points of the S-shape exceed the workspace of a mini five-axis CNC milling machine, this study reduced its size to 15% of the original, ensuring it fits within the machining limits. The final adjusted shape, including fixtures, is depicted in Figure 4. The computer-aided manufacturing program was created using the Fusion 360's manufacture module. Peripheral milling with a 6 mm 4-flute, and a 30° High-Speed Steel (HSS) end mill was used to machine the S-shaped part. The machining parameters were set at a cutting speed of 100 m/min and a feed rate of 200 mm/min. Subsequently, a simulation was conducted, and NC code was generated for the actual machining process, as portrayed in Figure 4.

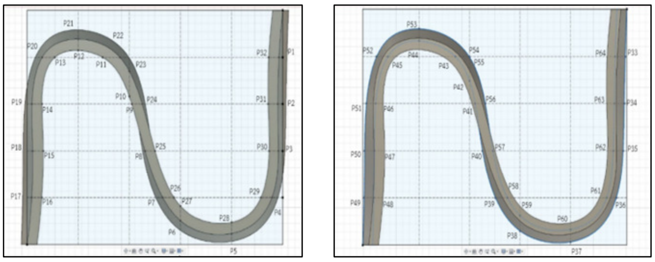


Fig. 3. S-shaped for measurement 64 points: (a) the plane Z = 0, (b) below plane Z = -12.

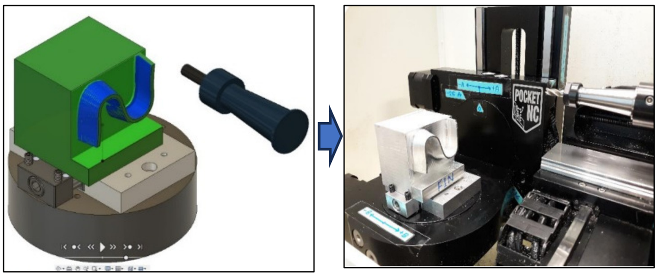


Fig. 4. CAD/CAM of an S-shaped part milled on a mini five-axis machine tool.

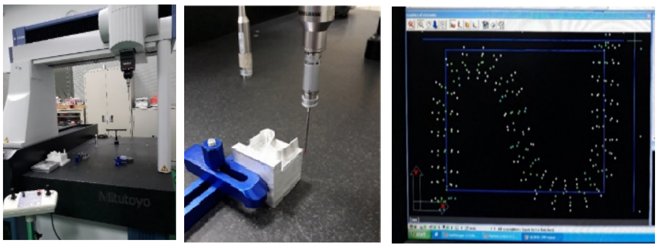


Fig. 5. CAD/CAM of an S-shaped part milled on a mini five-axis machine tool.

2) S-Shaped Measurement

The S-shaped measurement experiment detailed in Figure 5 involved measuring sixty-four points on the workpiece using a Mitutoyo Coordinate Measuring Machine equipped with the GEOPAK software. Thirty-two points were situated above the 0 plane, whereas the remaining thirty-two were below the -12 plane. Prior to compensation, the standard deviations are 0.082 mm, 0.041 mm, 0.233°, and 0.454° for X, Y, A, and B axes, respectively. After compensation, the standard deviations decreased to 0.041 mm, 0.017 mm, 0.099°, and 0.275° for the X, Y, A, and B axis, respectively. These measurements were then analyzed to determine the mean error and standard deviation for the X, Y, A, and B axes.

D. Improvement of NC Programs

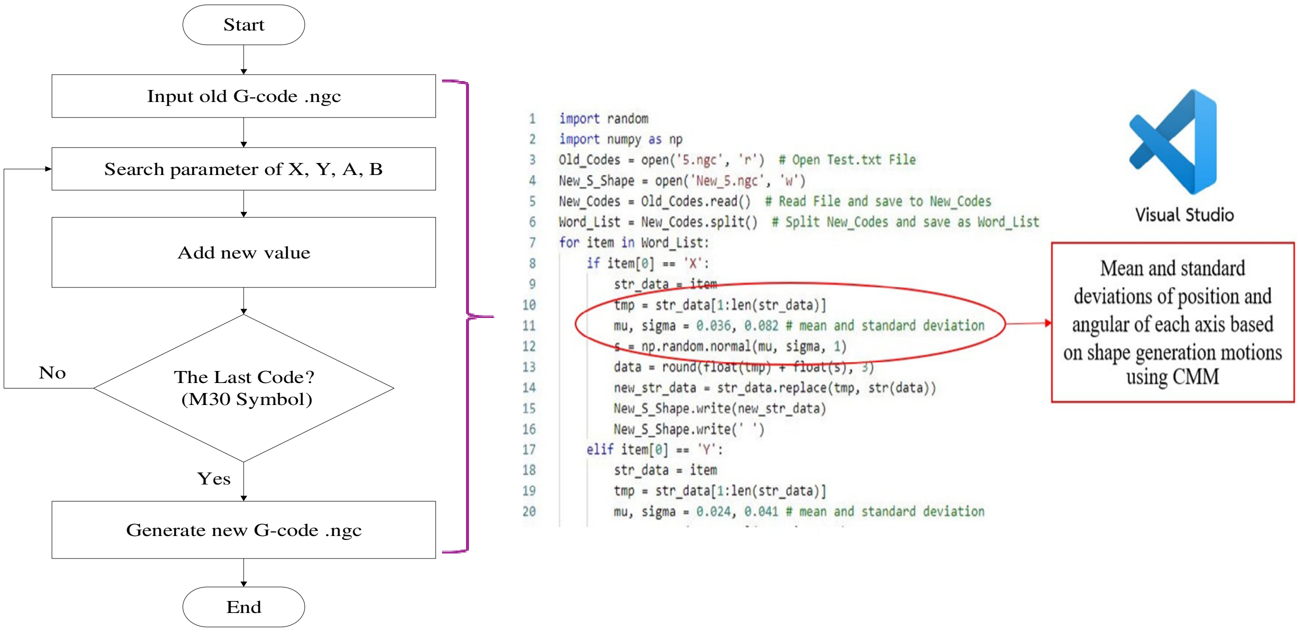
1) Improvement of NC Programs through Shape Generation Motion Analysis

The NC program for the S-shape milling process is improved by obtaining the original NC code data from the CAM program and compensating them based on motion deviations observed during virtual machining. This compensation addresses kinematic motion deviations, geometrical coordinate system errors, and deflection at the end mills of mini five-axis CNC milling machines.

A new NC code is then generated for milling the S-shape, with the variable values adjusted according to the pre-compensation workpiece errors, in compliance with ISO 230-1 standards. Prior to the cutting experiment, it is essential to obtain the corrected NC codes. This research utilizes a method based on shape generation motion deviations for error compensation, as depicted in the flowchart in Figure 6. The NC code improvement program is subsequently developed using the Python programming language.

The original NC code data are acquired from the CAM program in the form of an ngc file, and the program extracts the NC codes associated with the variables X, Y, A, and B. These variables are then compensated based on the shape generation motion of virtual machining, addressing kinematic motion deviations, the geometrical coordinate system, and deflection at the end mills, specifically for mini 5-axis CNC milling machines. Finally, the revised CNC code for the variables X, Y, A, and B is adjusted to enhance accuracy in milling the S-shape model, as illustrated in Figure 6.

The parameters in (8) are obtained from a small five-axis CNC milling machine and are as follows: a tool diameter of 6 mm, a workpiece material of aluminum A7075, a depth of cut of 0.5 mm, a feed rate of 1000 mm/min, and a spindle speed of 5000 rpm. The specific coordinate positions among the axes are: d_1y = -21.1734 mm, d_2x = 75 mm, d_2y = 21.1734 mm, d_3x = 1 mm, d_3y = -44.823 mm, d_3z = 20.455 mm, d_4z = 161.76 mm, d_4x = -12.5 mm, d_4y = 50.99 mm, d_5z = 29.05 mm, d_5y = 57.333 mm, d_6z = -53.7 mm, and d_7z = -76 mm. The cutting strength coefficients in (4) are K_{Tc} = 937.334, K_{Te} = 5.0386, K_{Rc} = 292.067, K_{Re} = 6.7597, K_{Ac} = 171.37, K_{Ae} = -0.83067, and E = 200 Gpa.



```
import random
import numpy as np
Old_Codes = open('5.ngc', 'r')  # Open Test.txt File
New_S_Shape = open('New_5.ngc', 'w')
New_Codes = Old_Codes.read()  # Read File and save to New_Codes
Word_List = New_Codes.split()  # Split New_Codes and save as Word_List
for item in Word_List:
    if item[0] == 'X':
        str_data = item
        tmp = str_data[1:len(str_data)]
        mu, sigma = 0.036, 0.082 # mean and standard deviation
        s = np.random.normal(mu, sigma, 1)
        data = round(float(tmp) + float(s), 3)
        new_str_data = str_data.replace(tmp, str(data))
        New_S_Shape.write(new_str_data)
        New_S_Shape.write(' ')
    elif item[0] == 'Y':
        str_data = item
        tmp = str_data[1:len(str_data)]
        mu, sigma = 0.024, 0.041 # mean and standard deviation
```

Fig. 6. Flowchart of NC program improvement based on shape generation motions.

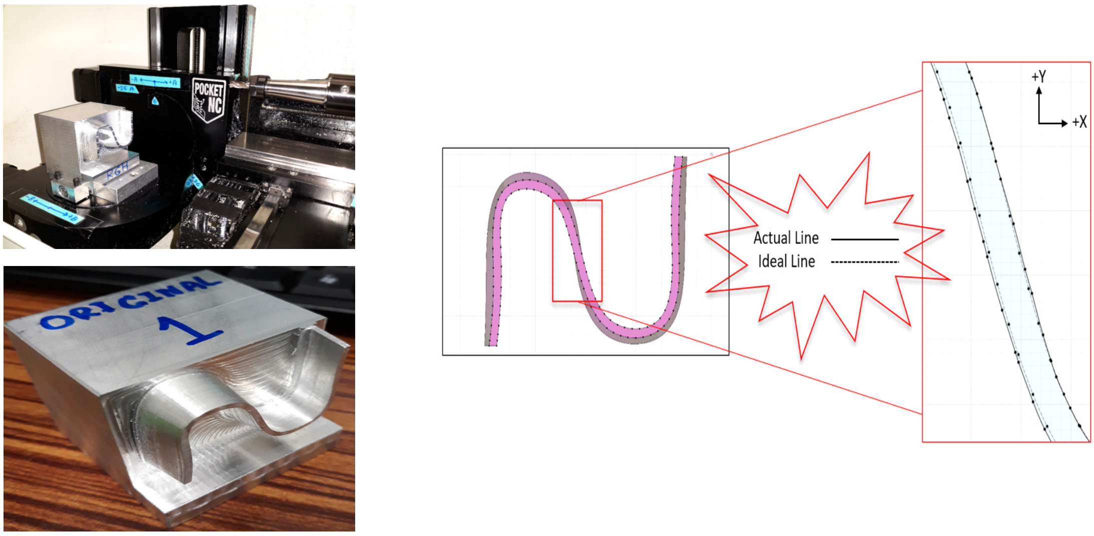


Fig. 7. Machining S-shaped part based on shape generation motion deviations.

These parameters are transformed into the final cutting-edge positions by incorporating geometric error parameters, which are randomly distributed based on normal distributions. Iterating this process at each cutting-edge location of the cutting tool inserts enables the generation of the entire surface of the milled part.

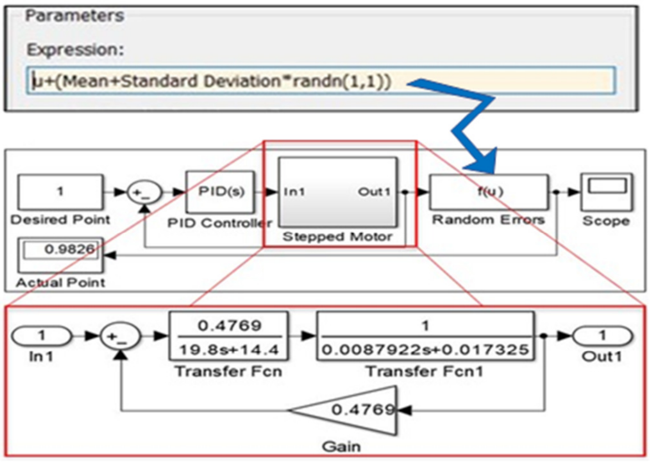
2) *Improvement of NC Programs with Feed Drives Control Analysis*

The closed-loop feed drive system in a five-axis CNC machine tool integrates various feedback control methodologies, such as PID controllers, along with feed-forward friction compensation. Additionally, it introduces a simplified linear model for feed drives employing PID control [36]. A typical ball screw drive system comprises several components, including a current amplifier, servomotor, lead screw coupling mechanism, preloaded ball screw and nut, workpiece-holding table, guideway friction elements, and feedback sensors. To achieve direct drive feed mechanisms, the ball screw drive and rotary servomotor can be replaced with a linear motor and bearings. Control commands for each axis determine the overall response of the feed drive transfer function, which encompasses components like a Digital to Analog (D/A) converter, amplifier, servomotor, inertia, viscous damping, guideway friction, and lead screw backlash. Each axis may incorporate acceleration, velocity, and position sensors, with specified parameters for accuracy and noise [37].

The linear dynamics of feed drive mechanisms are also considered in the virtual machining system. The linear dynamic model of a standard feed drive includes the axis controller, which generates a control signal applied to the current amplifier, with a gain of K_a. The motor armature produces dynamic torque T_m, assumed to be linearly proportional to the motor current, defined by the motor torque constant K_t. This study does not take into account external disturbance torque T_d. The determination and integration of accelerating the inertia and overcoming viscous damping in the motor shaft are also considered. Subsequently, these factors are used to calculate the angular position q. The angular position of the motor shaft is then converted into the linear displacement of the table via the ball screw and nut mechanism, characterized by a transmission gain of r_g [37]. The angular velocity of the motor shaft and the actual position of the table in the Laplace domain are calculated by:

$$\omega\,(s) = \frac{1}{Js+B}\,[K_t K_a\,\mu_a\,(s) - T_d\,(s)] \tag{9}$$

$$x_1(s) = \frac{r_g}{s}\,\omega\,(s) = \frac{r_g}{s}\frac{1}{Js+B}\,[K_t K_a\,\mu_a\,(s) - T_d\,(s)]$$



Expression: u+(Mean+Standard Deviation*randn(1,1))

$\frac{0.4769}{19.8s+14.4}$

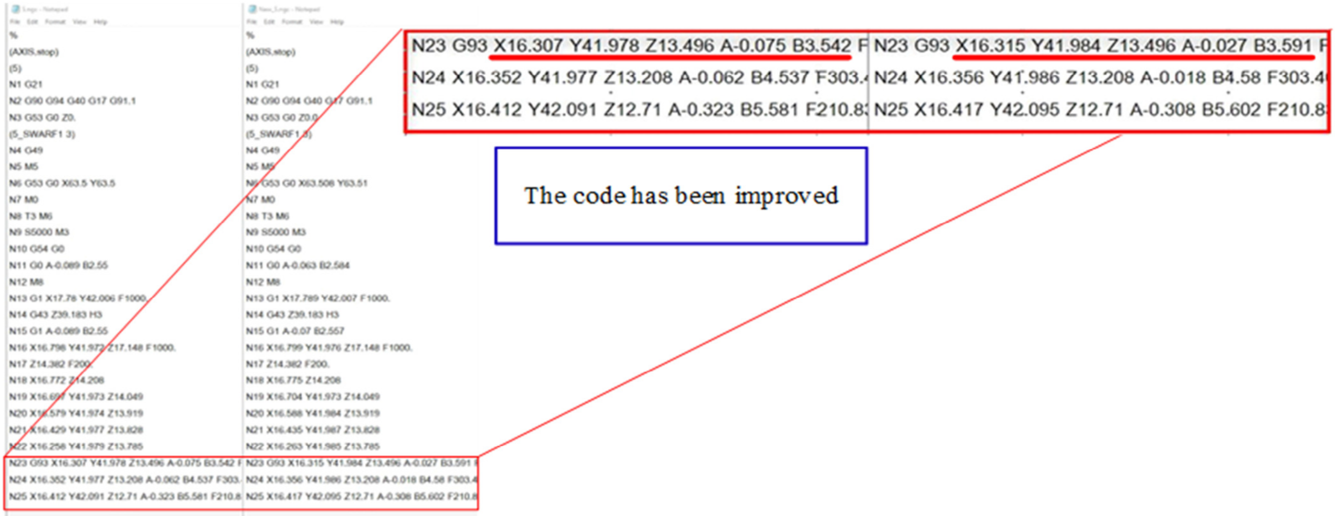
$\frac{1}{0.0087922s+0.017325}$

Fig. 8. The closed-loop system with PID control of linear feed drives.

The closed-loop PID control system leverages feedback control based on sensor data to provide real-time values. However, as small 5-axis CNC milling machines are unable to accommodate sensors, this investigation seeks to develop a control model utilizing Simulink software. This model incorporates gain tuning to enhance the motor's performance. The motor parameters and transfer function values were derived from prior research [37]. Figure 8 presents the closed-loop system with PID control, which employs feedback control to evaluate the position and angular errors of each axis based on shape generation motion and random errors. The PID control system necessitates the manual adjustment of its parameters to prevent overshoot and achieve the setpoint as rapidly as possible. The tuned parameters for the system are 2, 2, and 0.5, for *P*, *I*, *D,* respectively and the filter constant (*N*) is 100.

3) NC Program Quality based on Shape Generation Motions and Feed Drives

The NC program for machining S-shaped parts has been improved through the implementation of a virtual machining simulation. This simulation incorporates shape generation motion, which is followed by the refinement of position and angular adjustments using a closed-loop system with PID control. This process allows for the optimization of the machining parameters, resulting in more precise and efficient S-shaped part production. Figure 9 illustrates the newly adjusted G-codes based on these optimized parameters.



```
%
(AXIS,stop)
(5)
N1 G21
N2 G90 G94 G40 G17 G91.1
N3 G53 G0 Z0.
(5_SWARF1 3)
N4 G49
N5 M5
N6 G53 G0 X63.5 Y63.5
N7 M0
N8 T3 M6
N9 S5000 M3
N10 G54 G0
N11 G0 A-0.089 B2.55
N12 M8
N13 G1 X17.78 Y42.006 F1000.
N14 G43 Z39.183 H3
N15 G1 A-0.089 B2.55
N16 X16.798 Y41.972 Z17.148 F1000.
N17 Z14.382 F200.
N18 X16.772 Z14.208
N19 X16.697 Y41.973 Z14.049
N20 X16.579 Y41.974 Z13.919
N21 X16.429 Y41.977 Z13.828
N22 X16.258 Y41.979 Z13.785
N23 G93 X16.307 Y41.978 Z13.496 A-0.075 B3.542 F
N24 X16.352 Y41.977 Z13.208 A-0.062 B4.537 F303.
N25 X16.412 Y42.091 Z12.71 A-0.323 B5.581 F210.8
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%
(AXIS,stop)
(5)
N1 G21
N2 G90 G94 G40 G17 G91.1
N3 G53 G0 Z0.0
(5_SWARF1 3)
N4 G49
N5 M5
N6 G53 G0 X63.508 Y63.51
N7 M0
N8 T3 M6
N9 S5000 M3
N10 G54 G0
N11 G0 A-0.063 B2.584
N12 M8
N13 G1 X17.789 Y42.007 F1000.
N14 G43 Z39.183 H3
N15 G1 A-0.07 B2.557
N16 X16.799 Y41.976 Z17.148 F1000.
N17 Z14.382 F200.
N18 X16.775 Z14.208
N19 X16.704 Y41.973 Z14.049
N20 X16.588 Y41.984 Z13.919
N21 X16.435 Y41.987 Z13.828
N22 X16.263 Y41.985 Z13.785
N23 G93 X16.315 Y41.984 Z13.496 A-0.027 B3.591 F
N24 X16.356 Y41.986 Z13.208 A-0.018 B4.58 F303.4
N25 X16.417 Y42.095 Z12.71 A-0.308 B5.602 F210.8
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N23 G93 X16.307 Y41.978 Z13.496 A-0.075 B3.542 F
N24 X16.352 Y41.977 Z13.208 A-0.062 B4.537 F303.
N25 X16.412 Y42.091 Z12.71 A-0.323 B5.581 F210.8
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N23 G93 X16.315 Y41.984 Z13.496 A-0.027 B3.591 F
N24 X16.356 Y41.986 Z13.208 A-0.018 B4.58 F303.4
N25 X16.417 Y42.095 Z12.71 A-0.308 B5.602 F210.8
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Fig. 9. NC program improvement based on shape generation motions and feed drives.

The S-shaped workpiece was meticulously measured at 64 discrete points using a high-precision coordinate measuring machine to determine the error distances between the nominal, computer-generated design profile, and the actual machined part. The comprehensive results demonstrate a remarkably high degree of compatibility and fidelity between the virtual model and the physical, as-manufactured component.

III. RESULTS

After conducting an experiment the workpiece was analyzed for form errors using a CMM. The focus of the analysis was on determining the mean error values and standard deviations for the X, Y, A, and B axes, where a smaller standard deviation indicates higher workpiece quality. Figures 10 and 11 illustrate the comparison of errors along the X and Y axes for the S-shaped test pieces, highlighting the benefits of the compensation strategy applied to the improved NC program with shape generation motion through the feed drive system. On the X axis, the implementation of the compensation strategy led to a notable enhancement in form accuracy, as the standard deviation of form errors decreased from 0.0821 to 0.0171 mm, indicating more consistent deviations and improved workpiece accuracy.

Similarly, for the Y-axis, the form errors before and after modifications are depicted, with pre-modification errors identified by the blue line and post-modification errors by the red line. Initially, the standard deviation was 0.0797 mm, reflecting significant non-uniform deviations and lower accuracy. Following the modifications, the standard deviation reduced dramatically to 0.0041 mm, demonstrating much more uniform deviations and higher accuracy in the workpiece quality. These results underscore the effectiveness of the compensation strategy in improving NC program quality, as evidenced by the reduced standard deviations and enhanced form accuracy of the machined workpieces. Figures 12-13 showcase the angular errors of the A and B axes, comparing the application of a compensation strategy to an improved NC program with shape generation motions via the feed drive system. The angular error values of the A-axis before adjustment are represented by the blue line, while the post-adjustment values are represented by the red line. Before improvement, the standard deviation was 0.0040 rad; after improvement, it decreased to 0.00072 rad, indicating enhanced workpiece quality following the NC program adjustment. Similarly, the angular errors of the B-axis are depicted by the blue line for pre-adjustment values and the red line for post-adjustment values. Before improvement, the standard deviation was 0.00792 rad, decreasing to 0.002485 rad after improvement, suggesting an enhancement in workpiece quality.

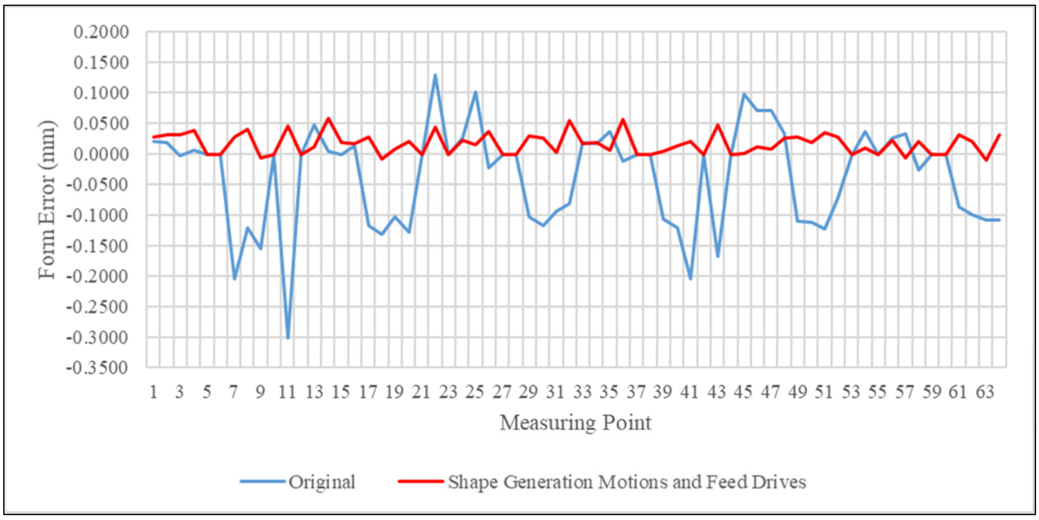

Fig. 10. Comparison of form errors along the X-axis.

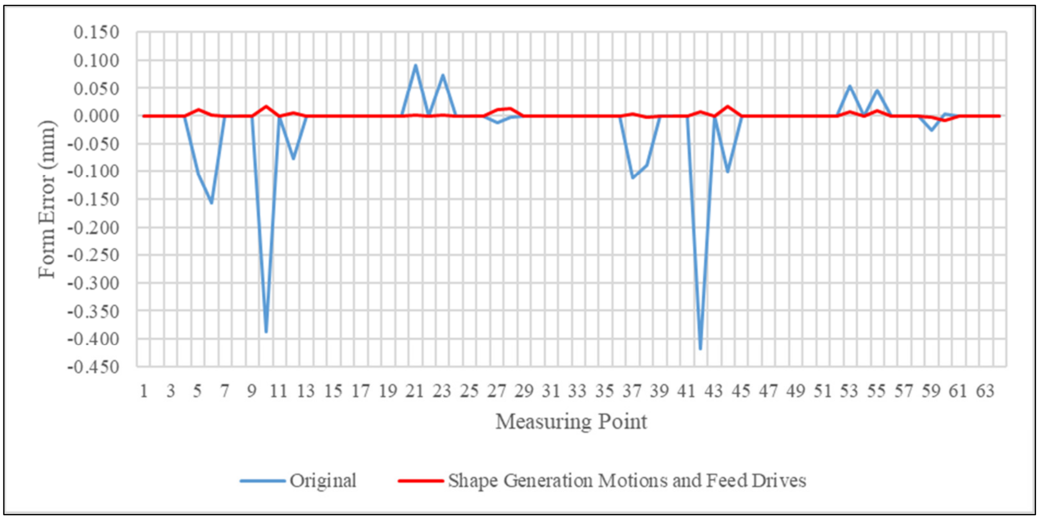

Fig. 11. Comparison of form errors along the Y-axis.

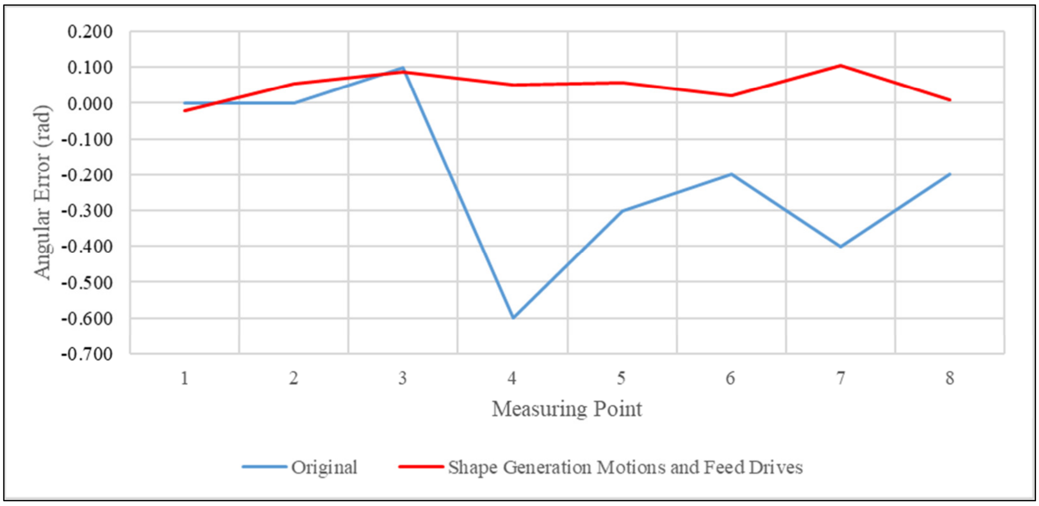

Fig. 12. Comparison of angular errors along the A-axis.

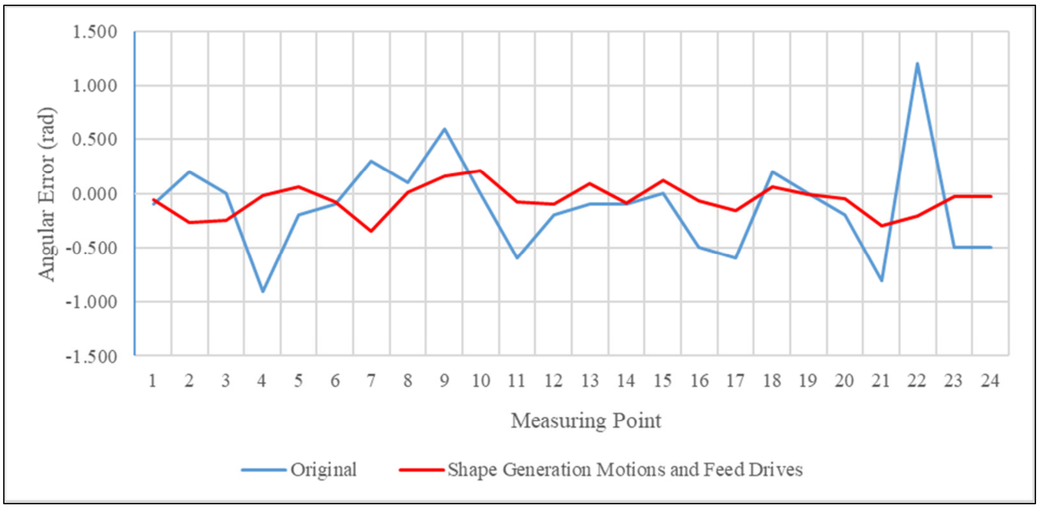

Fig. 13. Comparison of angular errors along the B-axis.

IV. CONCLUSIONS

The goal of the present study is to enhance the accuracy of NC programs generated by CAD/CAM systems, ultimately increasing productivity. A structured approach has been proposed to compare the standard deviation errors in NC program quality before and after the improvements. The key benefits of the new approach are:

This research aims to enhance the quality of Numerical Control (NC) programs by integrating shape generation motions from virtual machining with a closed-loop system employing Proportional-Integral-Derivative (PID) control on five-axis Computer Numerical Control (CNC) machine tools. The primary aim is to improve the accuracy of NC programs generated by Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM) systems, ultimately leading to increased productivity. Additionally, a systematic approach has been proposed to compare the standard deviation errors in NC program quality before and after the proposed improvements. The key benefits of this novel methodology are:

1. Shape Generation Motion Analysis: A mathematical technique utilizing a 4x4 Homogeneous Transformation Matrix (HTM) is employed to model shape generation motions. This approach integrates kinematic deviation data from a small five-axis CNC milling machine and cutter deflection information from virtual machining, alongside a closed-loop control system based on PID controllers. Achieving high form accuracy, especially when machining S-shaped workpieces, is crucial for practical machining processes. Consequently, a shape generation motion model was developed to assess the impacts of geometric errors on the precision of the machined S-shape, thereby ensuring enhanced accuracy.
2. Error Compensation and NC Code Generation: The proposed approach utilizes error compensation techniques to develop an enhanced NC code. This modified NC code is then employed for actual machining and measurement processes using a Coordinate Measuring Machine (CMM). The method primarily focuses on identifying and rectifying the key geometric errors associated with each axis during the machining of the S-shaped workpiece. An experiment was conducted to validate the feasibility and effectiveness of this approach. The results indicate that incorporating the error compensation strategies into the NC code led to a substantial improvement in the standard deviation errors, with an approximate reduction of 80.73%. Specifically, the standard deviation errors for the X, Y, A, and B axes were reduced by 76.83%, 95%, 82.40%, and 68.72%, respectively. These findings demonstrate the effectiveness of the method in significantly enhancing the quality of the NC program.
3. Overall Method Validation: The proposed method demonstrates the effectiveness of leveraging virtual machining to identify and address kinematic motion deviations in order to enhance the quality of NC codes, particularly for five-axis CNC machine tools engaged in S-shaped machining. The results indicate that this approach accurately pinpoints key kinematic factors that can be targeted to improve machining accuracy. However, the study's primary focus on kinematic deviations suggests the need for future research to expand the scope of investigation, incorporating a wider range of error sources, such as feed drive system parameters, in order to further refine and strengthen the overall methodology.

This comprehensive approach to enhancing the quality of NC code represents a notable advancement in machining precision, particularly for complex five-axis CNC machining processes, where the generation of intricate shapes and the control of motion deviations are crucial factors in attaining high-quality end products.

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