International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 06 Issue: 07 | July 2019 www.irjet.net p-ISSN: 2395-0072

Accuracy Enhancement of CNC Turning by Linear Positioning Error Compensation

Gamal Ismail[1], Azza Barakat[2], Sherif Elatriby[3], Helmy Elzoghby[4]

[1]MSc Researcher, Mechanical Department, Faculty of Engineering-Helwan, Helwan University, Cairo, Egypt
[2]Professor, Mechanical Department, Faculty of Engineering-Helwan, Helwan University, Cairo, Egypt
[3]Associate Professor, Mechanical Department, Faculty of Engineering-Helwan, Helwan University, Cairo, Egypt
[4]Associate Professor, Electrical Power and Machines Department, Faculty of Engineering-Helwan, Helwan University, Cairo, Egypt

---***---

Abstract - *This paper proposes a systematic checking and compensation for positioning errors of turning CNC machine tools which is low cost and demands little time. The study aims to identify axes errors without the need to in-process sensing or laser measurements such as ball-bar or laser interferometer systems, the estimation of positional errors is based on an assessment of the target turning CNC Machine tool by checking a sequence of parts which manufactured on this machine by coordinate measuring machine (CMM) to determine a travel error in each axis. The error modelling depends on the measurement analysis of machined parts groups to identify the geometric linear displacement error and the cutting force induced error. By applying the linear regression; the mathematical equations can be obtained. A developed software application under windows used to perform off-line error compensation based on receiving mathematical models and reconstructing the part program (G-Code).*

Key Words: Computerized Numerical Control (CNC), Positional Errors, Error Compensation, Coordinate Measuring Machine (CMM), Part Program (G-Code), Linear Regression, Machine Accuracy.

1. INTRODUCTION

The target of manufacturers is always achieved by producing accurate dimensional parts which involved in the term of product quality, since CNC turning machine tools are widely used in industry for achieving productivity and quality; it must be calibrated and error-compensated to fulfil that issue, the accuracy of CNC machine tool directly depends on the positional accuracy of the cutting tool's paths relative to the part being machined. The accuracy of CNC machine tool is primarily affected the positioning errors caused by the wear of the machine elements such as ball screw, guide ways, bearings, etc. Traditional/old CNC machine tools are the most common machines that exposed to this type of errors. A large portion of the geometrical errors in parts is caused by linear positioning errors in the axes of motion on a machine tool. CNC lathes play an important role because they are one of the most widespread machinery in the industrial field, therefore, researchers were interested in finding multiple ways to compensate error for these machines. The compensation for motion error needs good mathematical models and measurement of the machine tools [1].

Chen et al. [2] presented a model that characterizes interactions among the subsystems of a computer numerically controlled (CNC) lathe. The model was combined with a cutting force model to obtain a comprehensive turning simulator that simulates the cutting forces and part dimensions.

Liu and Venuvinod [3] proposed a method of error compensation for CNC turning, the method depended on solely on post-process and on-machine measurements of parts previously machined on the same CNC lathe.

Li and Du [4] introduced a method for work-piece error analysis and compensation in turning. They used a fine-touch sensor with a Q-setter (FTS-Q) (also called quick touch setter) for determining the geometric error of the machine tool. Both thermal and cutting force error of the machine tool were estimated using a radius basis function (RBF) artificial neural network, the models used for total error compensation.

Vinod et al. [5] presented approach of real-time positioning error compensation for a turning machine. The study developed a module for real-time compensation of positioning error of an axis throw an open architecture motion controller using back propagation feed forward neural network. The mapping of positioning error carried out by using laser interferometer system; key network parameters of the trained neural network have been extracted and used in a 'C' program for real-time compensation of the positioning error based on the position of the axis by updating tool offset using global variable.

Araujo and Rolim [6] proposed systematics for checking straightness and perpendicularity errors in CNC lathes. The study depended on machining and metrological approaches; thermography of the specimens, scanning electron microscopy of cutting tools after machining, cutting force calculation according to Kienzle, computer simulation by ANSYS software, roughness measurement and measurement of machined pieces, they presented this checking systematics as an essential tool and an option for decision making when choosing more sophisticated testing methods.

Furthermore, many of the research papers have been provided to compensate errors of CNC machine tools over two axes.

Typically geometric errors identification in common engineering method requires high cost systems and demands long time; so the work in this research aims at improving the accuracy of CNC turning machines by providing simple systematic procedures that can be applied in the factory by engineers and users that would be useful for checking machine tools in the industrial field, as well as it can be applicable for small, medium or large-sized companies. The proposed error compensation technique for linear positioning is easy, flexible, costless and suitable for all CNC lathes. The assessment of CNC lathe has been carried out using a sequence of cutting tests without the need to in-process sensing or laser measurements such as ball-bar and laser interferometer systems. The measurements of cutting tests were conducted by a high precision coordinate measuring machine (CMM). The positional errors in X and Z axes were used to edit G-Code file by a developed software to reconstruct NC commands regards to error model algorithms.

2. MACHINE ASSESSMENT

The common way to determine the accuracy of a CNC machine tool is to measure the machined part's dimensions values and know how they differ from nominal values.

Errors identification relevant to this research depends on machining which performed on the target CNC machine tool, upon the desired dimensions of a machined part; the total dimensional error is approximately:

$\delta(\text{total})$ = Actual dimension – Nominal dimension (1a)

$\delta(\text{total}) \approx \delta$ [(geometric) + (thermal) + (cutting force)] (1b)

The methodology of testing and evaluating the machine tool based on sequence machining of parts that were prepared to be checked and measured thereafter. The evaluation process is based on two-stages of errors identification; first stage is geometric errors identification excluding influence of thermal or cutting force, second stage is errors identification that result from cutting conditions and thermal effect. Machining process take into account setting up the machine under standard specifications and required parameters, the machined parts is measured by precision/calibrated CMM; the analysis of measurement results provides determining the accuracy value or deviation which is derived from the interaction between machine tool error and cutting forces induced error including thermal error occurred during machining.

2.1 Geometric Error Determination

The geometric error of the machine tool is attributed to the inaccuracy of the machine tool and the cutter, the geometric errors can be described as the imperfections in the machine components that cause inaccuracy axis position related to the cutter, so the geometric error of the CNC machine tool can be obtained based on the measurements of axes movements with respect to an accurate reference.

Without the effect of cutting force induced errors and thermal induced errors; when bias is found to exist in a machining process or other process by, for example, tracking a dimension (diameter here) as a function of number of parts made on a control chart, the manufacturing conditions are adjusted to compensate for the bias to make the mean on the distribution agree with the nominal, the geometric error in two axes CNC machine tool (turning) can be computed as the difference between the nominal value and actual value of the axis movement. According to the equations:

$$\delta(x) = (X_{nom} - X_{act}) / 2 \quad (2a)$$

$$\delta(z) = Z_{nom} - Z_{act} \quad (2b)$$

If n-number of measurements have been done, where i= (1,2,……,n) then;

$$\delta(x_i) = (X_{i\text{-}nom} - X_{i\text{-}act}) / 2 \quad (3a)$$

$$\delta(z_i) = Z_{i\text{-}nom} - Z_{i\text{-}act} \quad (3b)$$

Total of six cuts have been done, five cuts for geometric errors determination of X-axis with different diameters (12, 18, 24, 30 and 36mm), Fig. 1 shows a design diagram of initial machined material with different diameter each cut used for X-axis geometric errors determination.

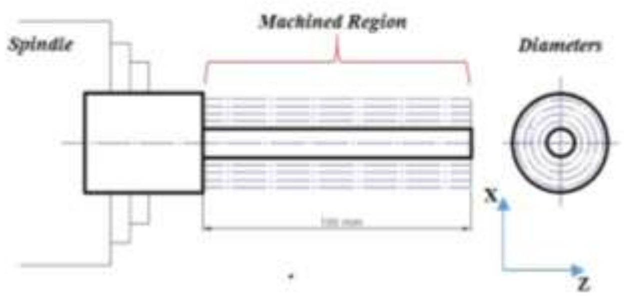

Fig -1: Illustration of machined part used for X-axis geometric errors determination.

One cut was used for geometric errors determination of Z-axis with different diameters that generate numbers of distances along Z-axis, Fig. 2 shows a diagram of machined part used for Z-axis geometric errors determination.

Fig -2: Illustration of machined part used for Z-axis geometric errors determination.

The machining process in geometric errors determination was carried out using cutting parameters; spindle speed = 300 rpm, feed rate = 0.1 mm/rev and depth of cut = 0.3 mm (level no. 1 for each parameter in table-3), these values have been selected to be an initial value for estimations and modelling of cutting force including thermal error model because these values have been selected to be the first cut in machining processes as illustrated in table-3 that were carried out for cutting force and thermal-induced error models.

EMCO PC TURN 55 CNC lathe was used to perform experiments, table-1 shows the technical data of the machine.

Table -1: Technical data of the lathe CNC machine tool.

Classification	Range	Unit
Travel X	48	mm
Travel Z	236	mm
Spindle speed	100 - 4000	rpm
Feed	0 - 2	m/min

Six cylindrical rods of aluminum 7075, 130 mm initial long with an initial diameter of 40 mm were used; five specimens used for X-axis geometric errors determination and one specimen used for Z-axis geometric errors determination, the machining process carried out to contain five different desired machined diameters along X-axis and five different desired machined distances along Z-axis.

Machining and design carried out for the purpose of obtaining functional relations between work-piece diameter and positional error of the axis travel, similarly obtaining functional relations between work-piece machined distances along Z-axis and positional error of the axis travel.

2.2 Cutting Force Error Determination

Since cutting force-induced errors depending on cutting process conditions represents a dominant role in error sources of a CNC machine tool, machine has been evaluated under changing of cutting conditions by cutting tests that carried out by the target machine, the machining of parts contained variety of cutting parameters for each cut, Fig. 3 shows the design of part used for tests.

Fig -3: Design of machined part used in machining tests.

Machine configuration and total eight cutting tests were conducted under different cutting conditions considering 3 factors (spindle speed (*n*), feed rate (*f*) and depth of cut (a)) at 2 levels as illustrated in table-2. The orthogonal array of interactions for the effects of cutting factors is illustrated in table-3.

Table -2: Assignment of levels to the factors.

Cutting Parameter	*Level*	
	I	*II*
Spindle Speed n (rev/min)	300	700
Feed Rate f (mm/rev)	0.1	0.2
Depth of Cut a (mm)	0.3	0.7

Table -3: Orthogonal array of cutting parameters interaction.

Test No.	*Spindle Speed (rev/min)*	*Feed Rate (mm/rev)*	*Depth of Cut (mm)*
1	300	0.1	0.3
2	300	0.1	0.7
3	300	0.2	0.3
4	300	0.2	0.7
5	700	0.1	0.3
6	700	0.1	0.7
7	700	0.2	0.3
8	700	0.2	0.7

Geometric positioning errors identification and modelling have been determined by identifying of measured deviations between nominal values and actual values; through the variation of cutting parameters in every cut, the influence of cutting factors with respect to machined part on its dimensions can be determined. The analysis of measured data used for creating the cutting force-induced error model.

2.3 Measuring

The measuring of machined parts was performed by Hexagon DEA Global Performance coordinate measuring machine (CMM) which has accuracy of 1.7 µm. Coordinate Measurement Machine (CMM) used to accurately determine and compare the dimension of the test parts that were created with and without the G-Code compensation to determine the improvements with the G-Code. CMM apply a wide variety of data collection modes including tactile scanning of geometric and freeform features, non-contact laser scanning, optical imaging and point-to-point (touch-trigger) measurement. A tactile scanning and point to point principle has been chosen for measuring process of cut tests because contact measuring method (touch-trigger) has higher precision than non-contact measuring (laser scanning or optical imaging). Furthermore, CMM contact measuring obtains the measuring values directly without need to extra analytical process that is necessary for non-contact measuring methods. For instant, the data captured from non-contact measuring is always cloud of points that has to be filtered by CAD software and converted to lines and planes to be used as a dimensional values.

3. ERROR MODELLING

3.1 Geometric Error Modelling

According to the measured data; the geometric error of X and Z axis was calculated by equations (3a) and (3b) regarding to the measuring positions of X and Z. For geometric errors in X-axis, the results of measurements gradient on the cylindrical surface of the diameter from the chuck to the end for each diameter have been obtained, the averages of values for each diameter have been calculated, with comparing to nominal values; the error data for each diameter can be calculated. Chart -1a shows the results of errors for diameters in micron.

Regards to the results; it is clear that the geometric error is proportional to the diameter dimension and approximately linear as shown in chart -1b.

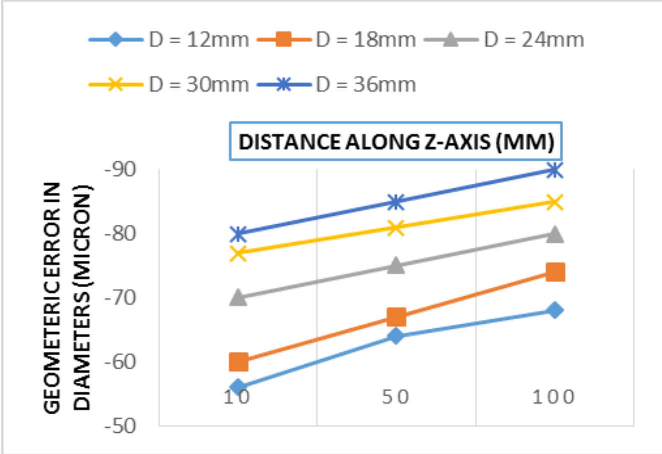

Chart -1a: Geometric error in diameters of X-axis.

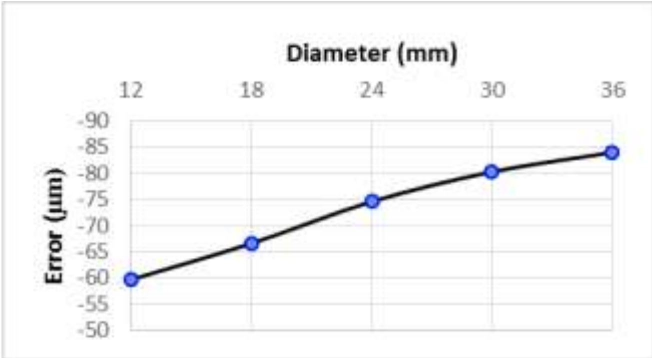

Chart -1b: Relation between the diameter and the error.

Likewise, the measuring results of the part that used in geometric error identification of Z-axis (five measures for each distance) has been illustrated in chart -2a, analyzing data and the average of measurements number for each distance has been calculated, indicating that the relation is proportional and approximately linear as shown in chart -2b.

Chart -2a: Geometric errors in Z-axis.

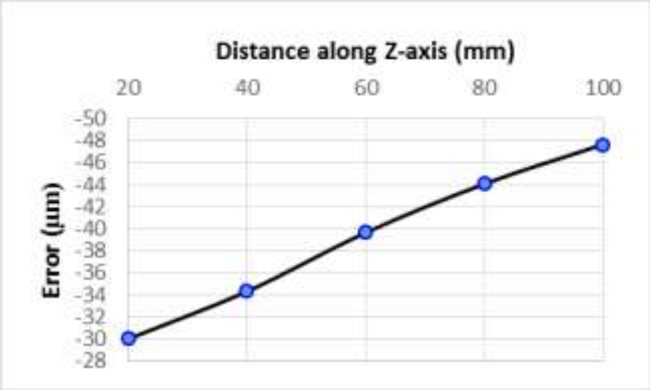

Chart -2b: Relation between the error and the distance along Z-axis.

3.1 Cutting Force Induced Error Modelling

Since the positional machining error due to the cutting force is proportional to the cutting force and the cutting force is influenced significantly and proportional to feed rate and depth of cut, thus the positional machining error is proportional to feed rate and depth of cut, whereas, cutting speed has an insignificant influence on cutting force [7-12]. But the cutting speed has a significant influence on cutting temperature; increasing of cutting speed lead to increasing in cutting zone temperature [8] that cause a percentage in positional error.

The result of CMM measurements for the diameter 30mm gradient on the cylindrical surface of the diameter from the chuck to the end for each cut test have been obtained, the averages of measurements of diameter for each test has been calculated, with comparing to nominal values; the error data for the diameter in each test has been calculated. Chart -3a shows the results of dimensional errors for the diameter in micron.

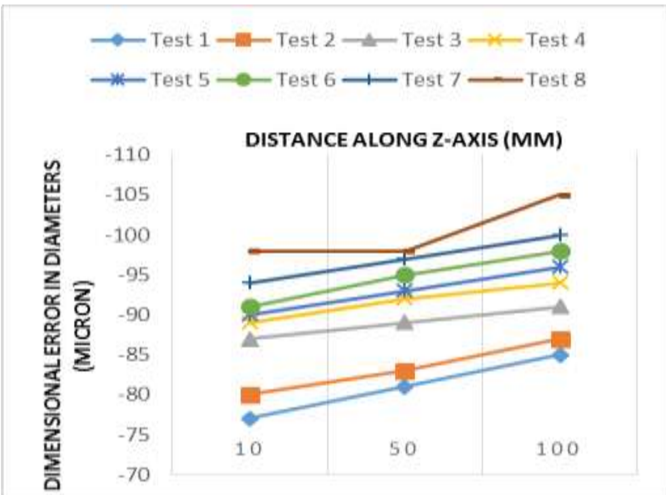

Chart -3a: Dimensional error in diameters along Z-axis.

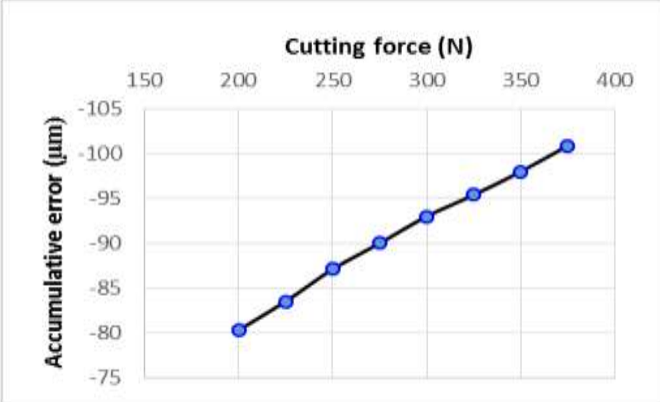

Chart -3b: The relation between cutting force and accumulative error in machine axes.

By estimation of cutting force for every cut test, the cutting forces have been obtained, the relation between cutting force and positional error in axes is approximately linear. Chart -3b shows the relation between cutting force and the dimensional error of the diameter. By analyzing the results and comparing with the results of geometric errors determination, the cutting force-induced error has been identified and modelled. The first cut with diameter 30mm and cutting parameters with test 1 in table-3 is the initial value of indication of the impact of cutting force including thermal deflection due to machining together on the dimensional error, by analysis and comparing data of all eight cut tests with changeable diameters machining data; the impact of cutting parameters has been assigned.

With the aid of graphically analysis, optimization and calculations; the absolute geometrical positioning error value of X and Z axes in linear motion can be obtained as – 47µm and – 26µm respectively, and the impact of cutting force on the dimensional positioning error in linear motion can be considered as – 13 µm increase in error per 100 N increase in cutting force.

By applying linear regression; the geometric error of X-axis, Z-axis and cutting force induced error can be modelled as the following equation:

$$\delta\,(g)_x = -\,0.00104\,D - 0.0481 \quad (6)$$

$$\delta\,(g)_z = -\,0.000217\,L - 0.0263 \quad (7)$$

$$\delta\,(F_c) = -\,0.00013\,F_c \quad (8)$$

Where:

$\delta\,(g)_x$ is geometric error of x-axis in mm.
D is the diameter in mm.
$\delta\,(g)_z$ is geometric error of Z-axis in mm.
L is the length of work-piece in mm.
$\delta\,(F_c)$ is the error due to cutting force in mm.
F_c is the cutting force in N.

4. ERROR COMPENSATION

The compensation process was carried out through modifying NC-code (part program) by a prototype software that has been developed under the ability of receiving the model algorithm and reconstructing NC commands in part program. The ideal tool path (tool tip and tool orientation) is generated from a CAD/CAM system or even hand-written, and then converted to NC codes in a post-processor. After that, loading the error measurement data and NC codes into the compensation software, every positional error parameter is identified at each tool tip, and then compensated in correspondingly modified NC codes. The flowchart of error compensation strategy is shown in Fig. 4.

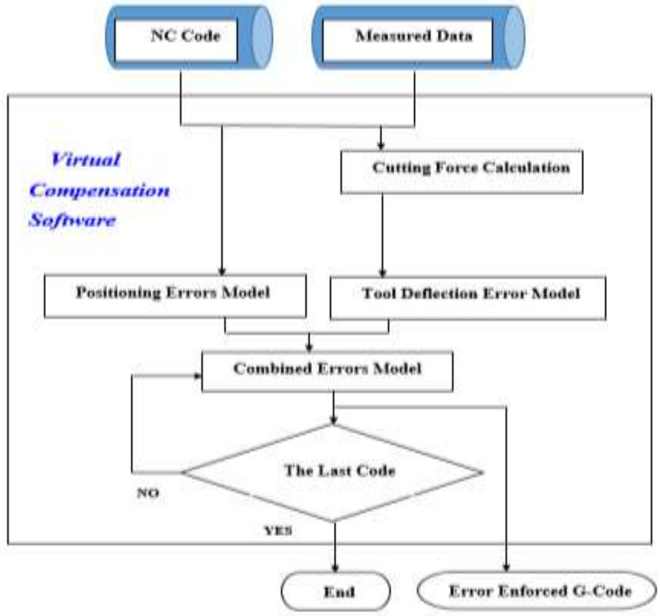

Fig -4: Flowchart of the positional error compensation strategy.

4.1 Compensation Model Validation

The model was validated by machining under different cutting conditions levels and comparing results between compensated and uncompensated processes. For validity of error compensation model taking into account geometric errors and cutting force induced errors; three cutting tests have been done without error compensation including variety of diameters and cutting conditions as illustrated in table-4, and the three cutting tests have been done with error compensation.

Table -4: Validation cutting tests and cutting conditions.

Test No.	*Diameter (mm)*	*Spindle Speed (rpm)*	*Feed Rate (mm/rev)*	*Depth of Cut (mm)*
Test 1	15	300	0.1	0.3
Test 2	20	500	0.15	0.5
Test 3	25	700	0.2	0.7

The dimensional measurements show that by applying the geometric error compensation, the machine accuracy has been improved and the compensation model is valid. Chart-4 shows the difference measurements of compensated and uncompensated cut diameters (ten times a measurement for each diameter distributed along Z-axis), the results show that the improvement is efficient with different diameters and different cutting conditions; the mean errors after compensation of test 1, test 2 and test 3 are -0.005mm, -0.0048mm and -0.0041mm respectively.

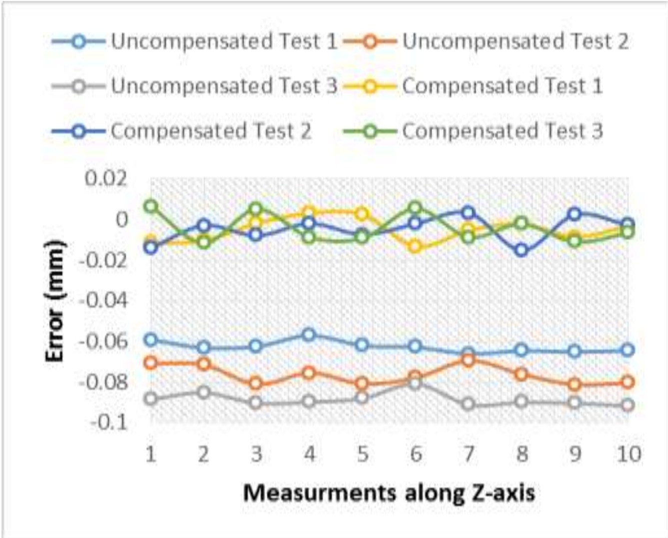

Chart -4: Error compensation of test 1, test 2 and test 3.

5. CONCLUSION

This paper proposed a methodology for improving the accuracy of turning CNC machine tools by linear positioning error compensation. The methodology was based on cutting tests that conducted by the target CNC lathe. The identification of errors depended on the measurements of cutting tests by CMM for determining/separating the positional errors and the errors due to cutting force of machining. Regarding to the linearity relation between axis travel and the error, aside from the linearity relation between the cutting force and the error; linear regression concept has been applied for obtaining the mathematical models for compensation. Error compensation software based on reconstructing part program (G-code) was developed for implementing the compensation process off-line. The compensation method has been implemented, and cutting tests were carried out to validate its practicability and effectiveness. The experimental results showed that the proposed method of error compensation is an effective way to improve the precision of machined parts and the machine's accuracy was significantly improved by 65%.

REFERENCES

[1] M. Rahman, J. Heikkala, and K. Lappalainen, "Modeling, measurement and error compensation of multi-axis machine tools. Part I: theory," International Journal of Machine Tools and Manufacture, vol. 40, no. 10, pp. 1535-1546, 2000.

[2] S.-G. Chen, A. G. Ulsoy, and Y. Koren, "Error source diagnostics using a turning process simulator," Journal of manufacturing science and engineering, vol. 120, no. 2, pp. 409-416, 1998.

[3] Z.-Q. Liu and P. K. Venuvinod, "Error compensation in CNC turning solely from dimensional measurements of previously machined parts," CIRP Annals-Manufacturing Technology, vol. 48, no. 1, pp. 429-432, 1999.

[4] X. Li and R. Du, "Analysis and compensation of workpiece errors in turning," International journal of production research, vol. 40, no. 7, pp. 1647-1667, 2002.

[5] P. Vinod, T. N. Reddy, S. Sajin, P. S. Kumar, and S. Narendranath, "Real-time positioning error compensation for a turning machine using neural network," Procedia Materials Science, vol. 5, pp. 2293-2300, 2014.

[6] R. Araújo and T. Rolim, "Systematics for checking geometric errors in CNC lathes," in Journal of Physics: Conference Series, 2015, vol. 648, no. 1, p. 012024: IOP Publishing.

[7] D. K. Sahu, P. K. Sen, G. Sahu, R. Sharma, and S. Bohidar, "A REVIEW ON EFFECT OF CUTTING PARAMETERS ON CUTTING FORCE IN TURNING PROCESS."

[8] Z. I. Korka, C.-O. Micloşină, and V. Cojocaru, "An Experimental Study of the Cutting Forces in Metal Turning," Analele Universităţii Eftimie Murgu Reşiţa. Fascicula de Inginerie, vol. 20, no. 2, pp. 25-32, 2013.

[9] J. Jadhav and B. Jadhav, "Experimental Study of Effect of cutting parameters on cutting force in turning process," International Journal of Innovative Research in Advanced Engineering, vol. 1, no. 6, pp. 240-248, 2014.

[10] R. Malagi and B. Rajesh, "Factors influencing cutting forces in turning and development of software to estimate cutting forces in turning," Int J Eng Innov Technol, vol. 2, pp. 14-30, 2012.

[11] D. Cica, B. Sredanovic, G. Lakic-Globocki, and D. Kramar, "Modeling of the cutting forces in turning process using various methods of cooling and lubricating: an artificial intelligence approach," Advances in Mechanical Engineering, vol. 5, p. 798597, 2013.

[12] D. Lazarević, P. Janković, M. Madić, and A. Lazarević, "Robust conditions for cutting force minimization in polyamide turning process," FME Transactions, vol. 43, no. 2, pp. 114-118, 2015.

BIOGRAPHIES

Gamal Ismail received the B.E. degree in Mechanical Engineering from Helwan University, Cairo, Egypt. He is currently pursuing MSc in Mechatronics Engineering in Faculty of Engineering at Helwan University. He was a Technical Engineer of CNC & CMM for several years specialized in Manufacturing of Pumps by Reverse Engineering. He is presently working as a Technical Manager/Consultant in the field of Pumping and Pneumatic Systems. His main areas of research interest are CNC, CMM, Robotics, Electronics & Control, Pumps & Compressors and Material Science.