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Variational analysis for CNC milling process

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Abstract

Dimensional and geometrical defects severely affect the quality of chip removal processes in CNC machines. In order to improve the accuracy, a long and expensive calibration process is usually performed on the CNC machine. The tuning process could be easier and faster if the designer is able to evaluate the effect of error sources providing a more robust and reliable CNC machine. The joined use of variational analysis and finite element analysis of geometrical features forecasts the position error of the tool tip.

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Keywords: Tolerance analysis; CNC milling machine; Finite element analysis; Tooltip deviation;

1. Introduction

Accuracy of machining process strongly depends on the ability in driving the machine tooltip along the nominal cutting path defined by the machine control system. In CNC machine, the nominal position of the tool tip derives from the preparatory function written in the ISO 6983 part program and interpreted by the Control unit, which drives the machine actuators and measures their positions.

The positioning errors of the tooltip is the result of different sources ranging from machine structure defects to control system inaccuracy, to deformation related to static and dynamic loads. Most of the error is usually recovered by means of machine calibration, an expensive and time-consuming procedure, which evaluates the distance between the actual and nominal position of the tool tip, and applies a compensation to the machine control system.

The calibration process could be faster and the machine process could be more accurate if the contributions to the position error of the tool tip are minimized according to an innovative design process where the different error sources are simulated and evaluated in order to forecast the best structure of the produced machine.

The modern Computer Aided Engineering tools allow for analyzing and simulating the behavior of complex systems, as the CNC machine is. CAE analyses can be used to evaluate the position error of the tooltip taking into account a defined set of error sources: geometrical defects, kinematic behavior, thermal deformation, static and dynamic loads.

In this paper, different CAE tools provide solutions to forecast the position error of the tooltip in a specific CNC machine when considering a set of error sources that affect the geometry of the machine and the position of its tooltip.

Broadly, machining errors depend on two major error sources: motion errors of the machine tool system and errors due to the machining process.

Major causes of errors in the machine tool system include imperfections and misalignments of guide-ways of the sliding stages. The assembly errors of the alignment of each axis, the non-parallelism of guide-ways and the profile errors of guide-ways affect the accuracy of. 3-axis machine tools and became more and more relevant in multi-axis machine tools, where the assembly error of the alignment of each axis is more significant.

Errors due to the machining process have a direct effect on the geometric accuracy of the machined surface. They include mainly cutting force variation, which cause tool deflection, and thermal effects, which deform the tool. Other sources of error are addressed in scientific literature [1].

A great number of researches related to tool error in cutting process had been conducted such as tool path and deflection

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modification model [2][3][4][5]. Furthermore, some investigation on kinematic model [6] and different models accounting for geometric and thermal errors had been done [7].

According to the scientific literature review, there is a gap in researches to investigate structural errors that affect tooltip deviation in milling process. Variation simulation analysis (VSA), kinematic model (KM) and FEM analysis (FEA) could be significantly merged to create models that figure out the possible position error of the tooltip in the working volume.

Determining the variations of the relative positioning of parts with tolerances in an assembly is a key problem in assembly planning [8] and mechanism design [9]. For example, nearly all assembly planners produce plans for nominal parts. However, because of shape and position variability due to manufacturing imprecision, the relative part positions vary as well. Thus, the nominal assembly plan might not be feasible for certain instances of parts, and a valid plan for one instance might not be suitable for others. In mechanism design, interference between two part instances can occur even when there is no blocking between the nominal parts.

Tolerance analysis is a critical step to design and build a product. Huge problems may present during the assembly process if the tolerance study on a subcomponent was not carried out or was ineffectual. These problems will introduce additional reworking time and product costs which are not compatible with today's industry requirements. It is even possible that the product design may have to be subsequently changed because of unforeseen tolerance problems not detected prior to actual assembly took place. In this case costs to the business will be very high. Many well-known approaches exist in the literature to tolerance analysis. The Direct Linearization Method (DLM) applies matrix algebra and root sum squares error analysis to vector loop based models to estimate tolerance stack-up assemblies [10]. The Variational solid modeling approach involves applying variations to a computer model of a part or assembly of parts [11]. The kinematics approach to model stack-up functions finds its roots in robotic; matrices similar to the homogeneous coordinate transform matrices are used to determine the resulting tolerance zones [12]. The Proportioned Assembly Clearance Volume (PACV) method creates 3D-dimension chains by using the Small Displacement Torsor (SDT) concept [13]. SDT is used to express the relative position between two ideal surfaces [14].

However, these methods are not easy to apply, especially for complex assemblies. So the aid of computer is called for. In the recent years, the development of efficient and robust design tools has allowed to foresee manufacturing or assembly problems during the first steps of product modeling by adopting a concurrent engineering approach. Today Computer Aided Tolerance Software is readily available [15]. The present work considers a CNC milling machine in order to study the influence of the tolerances assigned to assembly component in different position of the axis. This work uses Computer aided approaches in order to carry out a quick but reliable, evaluation of tolerance assignment. In the following, the case study is presented and, then, implementation methods of the analysis are given and results. Finally the obtained results are compared and discussed.

2. The case study

The machine assembly studied in the present work is the 3-axis Vertical Milling Machining Centers GX series illustrated in Fig.1. GX-Series machines are ideal for mold and die manufacturers, as well as precision engineers in the automotive, aerospace, medical and general engineering sectors.

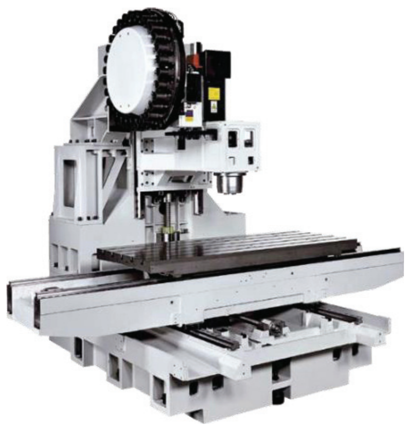

Fig. 1. Real GX series of CNC machines.

In our work we investigate on the GX1000 vertical machining center to provide a realistic simulation of position error of the tooltip taking into account different contributors, ranging from geometric defects to dynamic load.

Moreover, a simplified CAD model for given milling machine, see Fig.2, is provided to have fast but reliable result in evaluating the amount of errors due to geometric defects of machine components and their composition according to the kinematic behaviour of the machine itself.

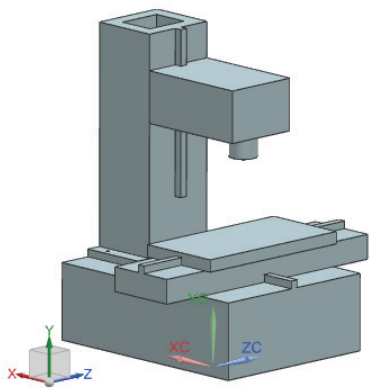

Fig. 2. Simplified model for VSA.

According to our work, the VSA and preliminary FEM analysis are implemented separately. We demonstrate accurate simplified model to transfer all the effective characteristic of the machine to have better FEM analysis, see Fig.3.

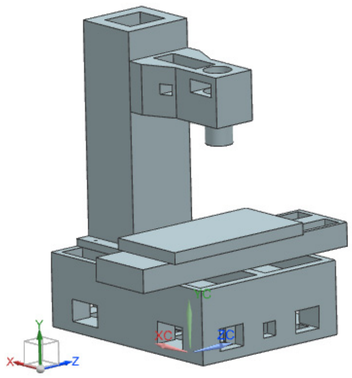

Fig. 3. Simplified model for FEM.

3. Methodology

The development of a comprehensive model for the analysis of several contributors to the position error of the tooltip is a cumbersome task. In order to reduce the time for the model construction while preserving the amount of information, we adopted a standard methodology available for the analysis of tolerances in manufactured parts.

3.1. Product and manufacturing information (PMI)

PMI conveys information such as geometric dimensioning and tolerancing (GD&T), 3D annotation (text), surface finishing and material specifications. PMI not only reduces the need to generate 2D drawings; it also enables downstream applications to directly access this information for automating tasks such as CNC programming, tolerance stack up analysis and CMM analysis.

Through the use of 3D documentation methods, the time and cost of documenting a part can be reduced by 50 percent and make early involvement of manufacturing easier with state of the art online 3D collaboration and visualization tools. In addition, because PMI is supported and published in the lightweight JT™ format, we can take advantage of the preferred method for visualizing data [16].

According to the PMI downstream procedure supported by Siemens software suite, the information applied to the CAD model of the CNC machine can be easily transferred to the simulation models.

3.2. Geometric Dimensioning and Tolerancing (GD&T)

According to the PMI approach, a complete set of dimensional and geometrical tolerances describes the errors admissible on the components of the CNC machine. Therefore it is possible to carry out a simulation of tool tip displacements taking into account the contributions of all the CAD components involved in the CNC machine. Although the GD&T model is applied to the real machine, the simplified model illustrated in Fig.3 is allows a faster analysis of error contributors. In Fig.4 we just illustrate the tolerances applied to the base of the CNC machine.

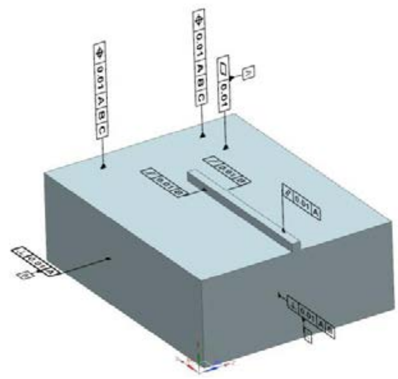

Fig. 4. Tolerance applied to the base of the simplified model of the CNC machine.

Table 1 illustrates a list of assigned tolerances for the simplified model. In spite of the cooperation with the producers of CNC machines, the real manufacturing data are rarely shared with research organism. In order to overcome such issue, we extrapolated the tolerance values from the general tolerances described in the standard ISO 2768. In spite of the obsolescence of the approach based on the general tolerances and the usually larger values provided by its application, such standard provides us a coherent definition of tolerance values and a qualitative outcome.

Table 1. Type and number of assigned tolerances to the simplified model.

Type of tolerance	Tolerance value	Number of tolerances
Position	ISO 2768	4
Flatness	ISO 2768	5
Parallelism	ISO 2768	17
Perpendicularity	ISO 2768	10

3.3. Kinematic analysis

The motion of the sliding stages along the guide-ways modifies the interaction of geometrical defects applied to the CAD models of CNC machine components. A reliable analysis of tooltip displacements should take into account the different positions of the sliding stages. Actually the software for the kinematic simulation of devices does not allow for such analysis. Due to software limitation, it is not possible to control the axes, to stop the tooltip at the specific point in the working volume, to run the variation simulation analysis (VSA). To overcome this limitation, we provide a transitory solution to keep our goal. Working volume encompasses limitless points. Furthermore, it is not feasible and is time-consuming procedure to take into account whole space to see in every point how much is the tool tip deviation. We apply a discretization of the working volume by considered 27 points located on three different surfaces along head transfer axis. Each surface contains 9 points, so the total number is 27. Fig. 5 illustrates the discretized working volume and its relationship with the whole machine.

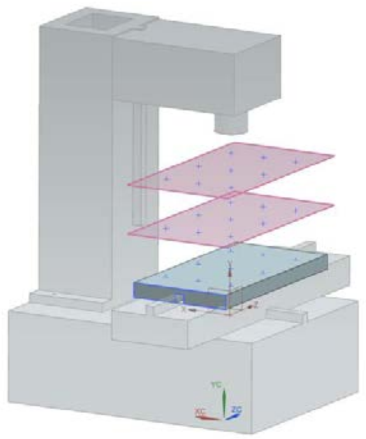

Fig. 5. Discretization of the working volume for the CNC machine

A kinematic chain creates a link from the tooltip, attached to the machine head, to the manufactured part lying on the machine table.

In order to create a closed link, which considers all the geometric errors involved in the kinematic chain, we have to connect the tool tip to the working table through cylinders of different heights (Z=0 mm, Z=270 mm, Z=540 mm). The distance between the tooltip and the cylinder represents the position error we measure with the VSA simulation.

Figure 6, illustrates three different configurations out of 27 ones has been provided.

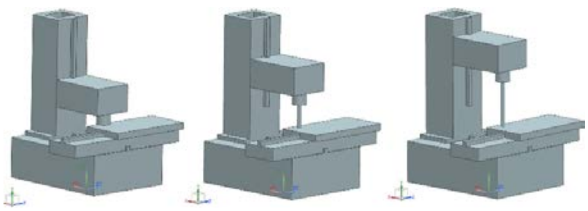

Fig. 6. Three different tool position with different height.

The GD&T model discussed in previous section, by means of the variation simulation analysis (VSA), evaluates the position error of the tooltip in the 27 points provided by the discrete kinematic model.

At the end of the simulation we have a result that is the merging of GD&T and Kinematic analysis of the CNC machine.

3.4. Thermal analysis

The thermal effects in the machining process are mainly concentrated on the tools, as demonstrated by different papers [17]. Continuous usage of a machine tool causes heat generation at the moving elements and the heat causes expansion of the various structural elements of the machine tool. The expansion of the structural linkage of the machine leads to inaccuracy in the positioning of the tool. Such errors are called thermal errors and may constitute a significant portion of the total error in a machine tool. Thus the overall volumetric error of a machine tool is not only dependent on errors due to the assembly and its specific kinematic structure but also on the thermal errors. Some of the possible heat sources are:

- Bearing
- Gear and hydraulic oil
- Drives and clutches
- Pump and motors
- Guideways
- Cutting action and swarf
- External heat sources

In a complete description of the behaviour of CNC machine, a finite element model of the machine should be developed to analyse the thermal deformation resulting from machine heating. The deformation of the CNC machine structure related to heating process of engines and friction should be evaluated in order to provide and accurate model. Nevertheless, a preliminary analysis of the deformation due to thermal effect demonstrates they are not relevant with respect to the other sources of errors (possibly due to our limited knowledge in the description of heating elements). The thermal analysis of the CNC structure will be developed in a future work.

3.5. Finite element analysis (FEA)

The present study develops a finite element model along with an end milling machine structure model to analyze the tooltip errors in the milling process of workpieces. The structure of tool milling machine is modeled with the CTETRA (4) mesh element that can more accurately simulate the geometry and structural behavior of the machine. The workpiece is not modeled here and we just consider the worst case configuration during milling process. This study neglects the dynamic effect during milling and assumes that the tool and the workpiece deform to their static equilibrium positions at any milling instant.

In Figure 3 we introduced the preliminary model for FEM analysis in order to see the effect of static loads on the tooltip position. We create the Assembly of FEM in order to have to whole part in their position respects to the other one. Figure 7 illustrates the a detail of the FEM models developed for finite element analisys.

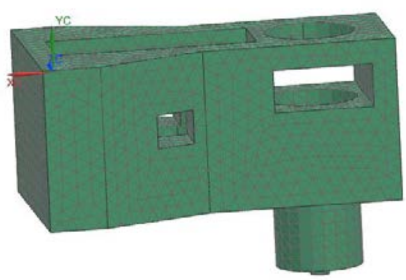

Fig. 7. FEM model of the head of the CNC milling machine.

According to the idea of integrating several error sources, the evaluation of the deformation generated by static and dynamic loads has to be performed along the whole working volume of the CNC machine. We are currently investigating the applicability of the analysis method proposed for sheet metal assembling by Liu [18] and Clement [19] and currently available in the industrial CAD software suites [16].

4. Results

The tooltip deviation due to geometrical deformation and defects is obtained be means of VSA tool. The total error of tooltip position with respect to the nominal position in the space is illustrated in Fig. 8. Moreover, for an improved visualization of results, we defined ±0.5 mm as an acceptable range of error.

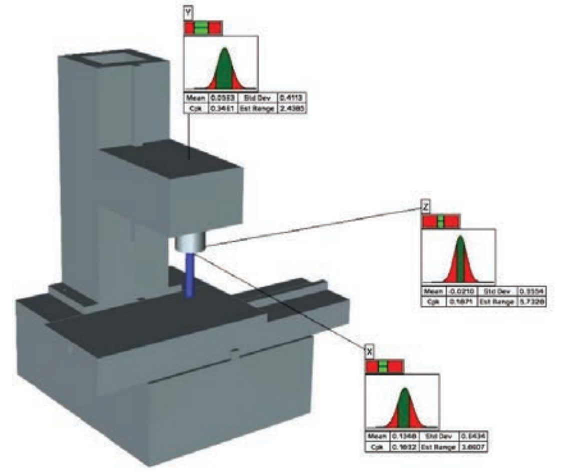

Fig. 8. Result of GD&T analysis VSA in a specific position of the tooltip (1 of 27 points)

According to the outcomes from GD&T model in Table 2, the most critical situation is in the Z direction where we have the lowest Cpk. The performance index Cpk considers the mean value and standard deviation respect to their nominal value, thus addressing the behavior of the attitude and the variability of the process.

Table 2. Position error of the tool tip along the three coordinate axis

Direction	Mean value (mm)	Standard deviation (mm)	Cpk
X	0.134	0.643	0.189
Y	0.056	0.411	0.346
Z	-0.021	0.955	0.167

The contribution of the different components to the final position error in the CNC machine configuration is illustrated in Fig. 9. Figure 9 and Table 2 are of the most important results of the VSA analysis. As it is clear, the highest contributor to the tooltip error is the lower table, which is assembled onto the base. Secondly, the upper body and its Guideways lead to a large amount of error, 21%. Thirdly, both working table and head have same effect on the tooltip deviation in working volume, 19%. Finally, the base and workpiece play a minor role with 4% and 1% respectively.

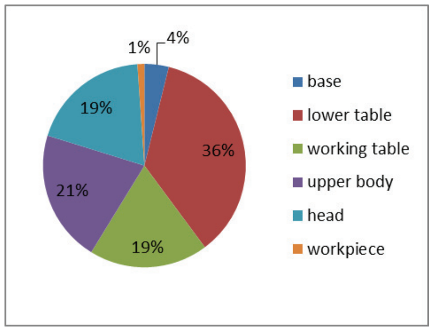

Fig. 9. Role of different contributors to the position error of the tooltip

Our main outcome consists of merging the results of GD&T and kinematic model. In our discretized working volume, in each specified plane we detect the point with highest error. As a result we could figure out the behaviour of the tooltip due to the geometrical defects, see Fig. 10.

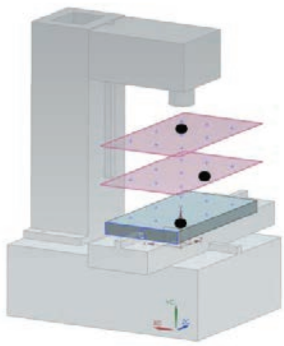

Fig. 10. Most critical zone in working volume

Also the preliminary FEM analysis demonstrates a relevant contribution to the position error of the tooltip.

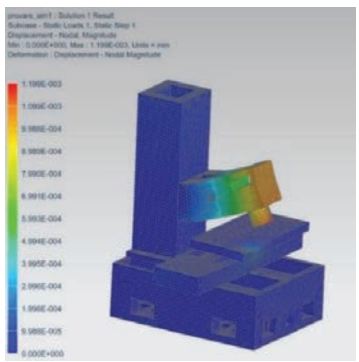

Fig. 11. Results of the preliminary FEM model.

Fig. 11 illustrates the effect of static loads on the head and the table of the CNC machine.

5. Conclusion and future work

In the paper the authors illustrates the analysis of tooltip positioning error in a CNC machine. Several error sources are analyzed to develop, during the design phase, the best solution to reduce the tooltip position error:

- Dimensional and geometrical tolerances
- Kinematic of CNC machine
- Thermal effects
- Static and dynamic loads

The paper illustrates, with different level of the detail, the different approaches for contributors analysis and their integration.

Further work is requested to provide a reliable industrial tool and the future investigation should be divides in two different paths:

5.1. Model improvement

The FEM model requires deeper investigation to simulate the effect of loads in the working volume of the CNC machine. According to the scientific literature, the solution could be derived from the Finite element analysis applied to sheet metal assemblies. Such solution is available in different CAD software suites, and allows for the analysis of stress and deformation in sheet metal parts under different constraints and loads. The adoption of such solution will evaluate the role of static and dynamic loads on the tooltip position error in the whole working volume of the CNC machine.

The FEM model should be effectively applied for the thermal analysis of the structure of the CNC machine. Currently the effect of heating seem to be less relevant than other sources of error, but it could be related to our pour modeling of heating sources.

The kinematic model requires a deeper analysis too. The current solution, relying on the discretization of the working volume, should be improved in order to carry out a complete analysis of kinematic consequences in the working volume of CNC machine.

Finally, we should improve the integration of the results of different analysis. Such integration is operating on GD&T and Kinematic analysis, but it should be improved in order to integrate FEA results.

5.2. Software improvement

During our work by mean of Siemens software, NX PLM and Teamcenter visualization, we figured out some technical limitations, which prevent us from fast and more flexible analysis. Our main goals in such area consist of the following improvements:

- Improve the PMI method to allow for a faster transferring of features and Tolerances from NX environment to the Teamcenter visualization.
- Link the JT file with the Process document to improve the application of modification in both the environments.
- Improve the kinematic assembly operation of Teamcenter visualization. It is necessary to control the axis motion and stop it to the desired position in order to perform a VSA analysis in any points of the working volume.

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