PREDICTION OF TOOLTIP ERROR IN CNC MILLING MACHINE BY USING VARIATION SIMULATION ANALYSIS (VSA) AND FINITE ELEMENT ANALYSIS (FEA)

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Abstract- The main objective of this research work is to study the tolerance analysis combined with Variation Simulation Analysis (VSA) and Finite Element Analysis(FEA) used to predict the position error of tooltip in CNC Milling machine (MT-250). For a given CNC machine 3D model is created then Geometric Dimensioning and Tolerancing model (GD and T) is applied to CNC mill structure. GD and T model is applied individually to each and every sub-component of milling machine such as base, lower table, working table, upper body, head. Variation Simulation Analysis (VSA) is used to predict the amounts and causes of variation. In order to find the tooltip displacement in given working volume kinematic analysis is combined with VSA analysis studied. In addition to above FEA analysis is also done on given milling machine. In static analysis deflection due to self-weight and in dynamic analysis (modal analysis) deflection at each node due to vibration are considered. Final result shows that the highest possible error point in the given work volume as well as roll of different sub-component on position error of tooltip was indentified. As per result the highest contributor to the tooltip error is lower table which is assembled to the base then upper body and head. Finally working table having major effect where as base and workpiece plays a minor role in position error.

Keywords- GD and T, VSA, FEA, Tolerance, kinematic analysis and Tooltip deviation..

I. INTRODUCTION

Dimensional and geometrical defects severely affect the quality of chip removal processes in CNC machines. In order to improve the manufacturing accuracy, a long and expensive calibration process is usually performed on the CNC machine. The 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 author has undergone thoroughly around 18 research papers relevant to machine tool error, geometrical, dimensional accuracy, sub-assemblies in error source of tooltip, Variation analysis capability, Process performance Index and Kinematic model results. From the papers he has indentified the research gap and formulated his research problem.

II. VARIATION SIMULATION ANALYSIS TECHNOLOGY (VSA) AND GD & T MODEL

VSA is a powerful dimensional analysis tool used to simulate manufacturing and assembly processes and predict the amounts and causes of variation. A digital prototype is used to create a comprehensive representation of geometry, product variation (tolerances), assembly process variation (sequence, assembly attachment definition, and tooling) and measurements.

In this work CNC MILL TRAINER MT-250has been considered which is shown in figure 1.1 as CAD model. The main assemblies are base, upper body, head, lower table and working table.

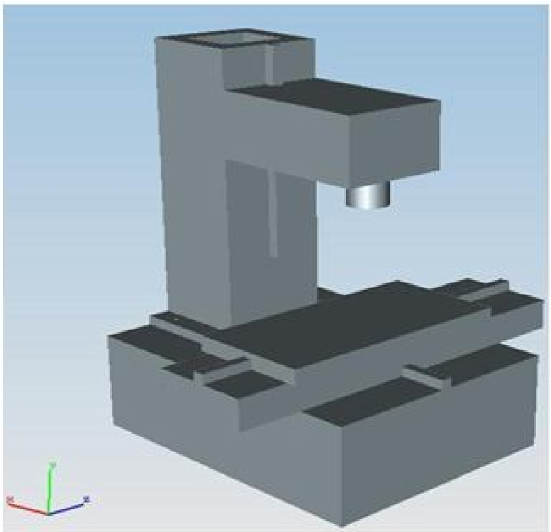

Figure 1.1: CAD model of tool machine

2.1 Implementation of Geometric dimensioning and Tolerencing (GD&T)

GD&T was implemented on CNC machine as per ISO 22768. According to the ISO 22768 there are different tolerances for different type of assigned symbols. Such as perpendicularity, flatness, straightness are shown in table 2.1 and 2.2.

Table 1.1: Straightness and flatness tolerances (mm)

Toleran ce Class	General tolerances of straightness and flatness					
	Up to 10	Over 10 up to 30	Over 30 up to 100	Over 100 up to 300	Over 300 up to 1000	Over 1000 up to 3000
H	± 0.02	± 0.05	± 0.1	± 0.2	± 0.3	± 0.4
K	± 0.05	± 0.1	± 0.2	± 0.4	± 0.6	± 0.8
L	± 0.1	± 0.2	± 0.4	± 0.8	± 1.2	± 1.6

Table 2.2: General Tolerances of perpendicularity (mm)

Tolerance class	Perpendicularity tolerances for fields of nominal lengths of the smaller side			
	Up to 100	Over 100 up to 300	Over 300 up to 1000	Over 1000 up to 3000
H	0.2	0.3	0.4	0.5
K	0.4	0.6	0.8	1
L	0.6	1	1.5	2

Consider class H for all the tolerances. Although, these numbers are not feasible from accuracy point of view for a precise tool machine but obtain an overall understanding about the effect of kinematic behavior and variational analysis in qualitative way.

III. KINEMATIC MODEL

The main description is to simply the model to have the kinematic behavior of the machine along the axis movement. In order to reach to the solution, defined the path which was applying tolerances to the 3-axis CNC milling machine to discover the amount of tool tip deviation from the nominal position. This working volume encompasses several points which are specified. Three different surfaces (Z=0, Z=150, Z=300) along head transfer axis that each of them has 9 points, totally 27 points. So by this method along with the Teamcenter visualization run the VSA analysis for different points.

IV. FINITE ELEMENT ANALYSIS (FEA) MODEL

The present study is to develop a finite element model in CNC milling machine to analyze the tooltip errors during machining. The CNC machine structure is modelled with ANSYS software. In this work static and dynamic analysis has been studied. The CNC milling machine base is fixed. Then displacement boundary conditions applied to the base. i.e. = UY = UZ =0 and rotations RX=RY=RZ=0. The displacement constrain applied in fixing the base area in all degrees of Freedom. The number of modes taken are six. Figure 4.1 shows deformation for mode 4 and table 4.1 shows the deformation and frequencies at each mode.

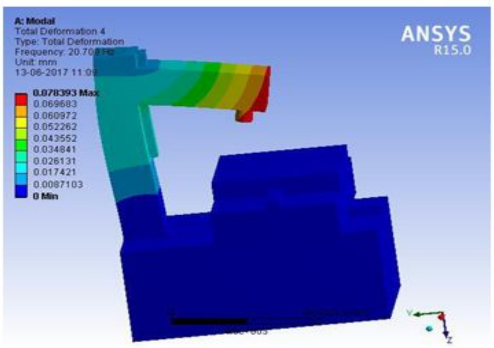

Figure 4.1: Deformation of FEA modal analysis

V. RESULTS AND DISCUSSION

5.1 GD and T results

Teamcenter visualization software used to indentified the total error of spindle position respect to the nominal position in the space and it is illustrated in figure 5.1.

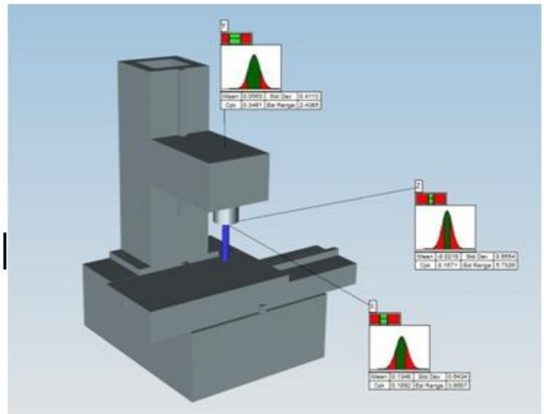

Figure 5.1: GD and T result

According to the results table 5.1 provides mean value, standard deviation and process performance index (Cpk). In Z direction Cpk have the minimum values highest mean value respect to the other directions. Furthermore, the large standard deviation in Z direction shows that the distribution takes place in a large range. To add, it is clear that in Z direction condition is worst and the error in this direction is more than the other direction. Another observation could be done to see the share of contribution for existed error by means of sub-assemblies. In table 5.2, shows the error contributors with their shares are given and it is clear that for each error in various directions there are different error sources with diverse magnitude.

Table 5.1 Parameters in 3 direction

Direction	Mean value(mm)	Std deviation	Cpk
X	0.117	0.575	0.171
Y	0.041	0.331	0.301
Z	-0.018	0.885	0.154

In every direction some part have minor share in the error source and the total amount of them are less than 1% as a result considered minimum zero share.

Table 5.2 Share of different assemblies in error creation

Direction	Base (%)	Lower table (%)	Working table (%)	Upper body (%)	Head (%)	Workpiece (%)
X	0	51.6	41.46	2.46	0	3.19
Y	0	55.49	30.99	7.38	5.84	0
Z	8.39	14.71	2.78	36.69	36.51	0

Table 5.3: Results of 27 points

5.2. Kinematic model Results

According to kinematic model provided in section 3 the mean and standard deviation which are obtained from the software compute the 3D mean and standard deviation for each point then calculate the Cpk in order to specify the worst points with largest error in each height. Table 5.3 shows all the results are provided for total 27 points. In table 5.4 the points with higher mean value and minimum Cpk value are indicated in dark black. The total error in these points is higher. For better visualized observation in figure 5.2, the highest errors in discussed points are represented.

According to the previous results, possible errors in three different directions cause by different parts with diverse values of contribution. Calculate the average of three axis and reached to the mean value of shares for each part in every height. In table 5.5 provides the share of each part in each height. From table 5.5 it is understand that in each height the effective part is lower table and less important part is the workpiece which is assembled on the work table. ie the base as the least effect on the tooltip deviation from the nominal position.

Table 5.4: 3D mean, Std deviation, Cp, Cpk

Points	3D mean	3D SD	Cp	Cpk
1	0.141	0.870	0.332	0.138
2	0.147	0.904	0.319	0.130
.				
7	0.221	0.810	0.356	0.115
.				
14	0.188	1.335	0.216	0.078
.				
27	0.182	1.915	0.151	0.055

Points	X direction				Y direction				Z direction			
	Mean	SD	Cp	Cpk	Mean	SD	Cp	Cpk	Mean	SD	Cp	Cpk
1	0.123	0.265	0.629	0.474	0.066	0.413	0.368	0.350	-0.02	0.718	0.201	0.193
2	0.138	0.273	0.611	0.442	0.051	0.412	0.394	0.329	-0.006	0.757	0.206	0.193
3	0.135	0.269	0.626	0.425	0.047	0.402	0.415	0.375	-0.008	0.757	0.205	0.217
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26	0.141	1.249	0.133	0.096	0.056	0.289	0.657	0.513	-0.041	1.426	0.117	0.107
27	0.168	1.259	0.136	0.097	0.052	0.288	0.694	0.519	-0.047	1.414	0.118	0.110

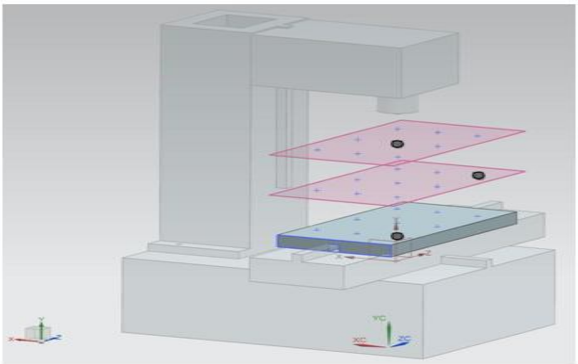

Figure 5.2 High possible errors in different heights

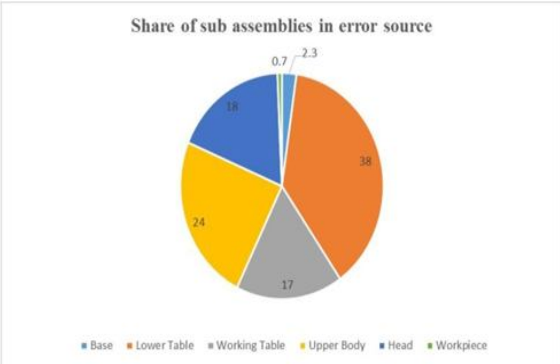

Figure 5.3: Pie chart of sub-assemblies share as error source of tooltip

The pie chart in figure 5.3 represents the overall share of each part in whole working volume according to the tolerances that are assigned to model. By this results, from most effective part to the least effective sub-assemblies are in this order: lower table, upper body, working table, head, base and the workpiece.

sub-assembly	Base	Lower table	Working table	Upper table	Head	workpiece
Total average in z=0	1.01	34.55	9.86	30.82	23.46	0.00
Total average in Z=150	2.17	36.59	19.88	24.57	18.34	1.06
Total average in z=300	3.50	43.96	23.28	18.77	12.72	1.05

CONCLUSIONS

This research work will provide the information about machine tool error, geometrical and dimensional accuracy and tolerance analysis. Several error sources are analysed to develop the best solution to reduce the position error of the tooltip. Lower Table is most dominating factor for position error of the tooltip. The least effective sub-assemblies are lower table, upper body, working table, head, base and the work piece. This shows tolerance on lower table as well as misalignment and non-parallelism of guide ways effect is high for position error of tooltip. The kinematic model shows the highest error point for Z=0 mm, Z=150 mm, Z=300 mm plane in the given working volume space. The FEA analysis gives deformation due to self-weight and vibration. The best solution to reduce the tooltip position errors by considering Dimensional and Geometrical tolerances, Kinematic of CNC machine, Static and Dynamic loads. This work may be extended FEM model improvement to simulate the effect of loads in working volumes, Thermal analysis of CNC structure and Improvement in kinematic model

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