Tool path quasi-static error simulation for a three axes machine tool using multi-body modeling

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Abstract— The improvement of the accuracy of milling machines is a key issue for machine tool manufacturers. Most of them solve the problem designing solutions that are stiffer and with higher damping, this however usually increases the cost of the machine itself. The general idea presented in this paper is to define a strategy for the prediction of the tool path deflection, this will allow a possible correction of the deflection thanks to a post-processing of the NC code. The proposed approach is mainly based on the simulation of the machine behavior and includes the inertia forces due to the axes movement, the gap on the axes, the deflection due to flexibility of the structure and the cutting forces. The model have been assembled using a commercial flexible multi-body software and has been validated thanks to experimental tests. The tuning of multi-body model input variables for tool-path correction has been carried out by a method of error sources synthesis and a DoE approach.

Keywords: Machine Tool, Flexible Multi-Body, Machining Accuracy

1. INTRODUCTION

In the past many aspects of the CNC machine have been studied by researches all over the world but only recently the topic of error modeling and compensation has been analyzed in detail in an attempt to enhance the accuracy of multi-axis CNC machine tools. The final objective was to understand, model and calculate the errors of the manufactured workpiece in order to verify the tolerances and, eventually, to reduce the errors and improve the accuracy. The main sources of these errors are the programming and interpolation algorithms, the driving mechanisms, the workpiece-tool and machine tool deflections due to the cutting forces, and the thermal deformations. Taking into account these sources many authors have proposed many methods to compensate the errors. Many use different strategies to evaluate the mean error of the machine in the work space, eventually creating an error map, and post process the data in order to use a fit compensation strategy, some instead use predictive approach to pre-process the tool-path data. Altintas et al., 2005, performed an accurate analysis of the state of the art of such approaches, the most interesting are the following. Anjanappa et al., 1988, developed a method for cutting force independent error compensation based on the assumption that the machine and workpiece could be considered as rigid bodies. Kiridena and Ferreira, 1994, focused their efforts on the analysis of the quasi-static errors of a machine tool and proposed a general kinematic model for the compensation of a three-axis machine tools. Srivastava et al., 1995, used the Denavit-Hartenberg transformation to build a compact volumetric error model, which considers the shape and joint transformations of inaccurate links and joints using small angle approximations. Suh, 1998, focused on the rotary table of five-axis machine tools and presented a complete error model for it. Ibaraki et al., 2010, also proposed some machining tests and measure procedures to define geometrical error for rotary axes using linear axes of the same machine, while Habibi, 2011, and Bohez, 2002, use laser interferometer device to evaluate tool-path error due to geometrical error of the linear axes. The approach proposed by Bohez is based on the closed loop volumetric error relations. Sakamoto et al., 1997, used a telescoping ball-bar to inspect and diagnose the error origins and Lei, 2009, investigated all possible combinations of linear and rotary axes performing ball-bar dynamic test in a five axis machine tool to eliminate gain mismatch errors of the control loop.

Some authors have also proposed methods to improve the accuracy thanks to a different control on the process parameters, for example Chuang and Liu, 1991, proposed an adaptive feed-rate control strategy based on estimated contour error so that the feed-rate could be adjusted adaptively. Yun and Jeon, 2000, proposed a feed-rate control approach that exploits the idea of inverse mapping, in which the relationship between contour error and feed-rate is identified using a multi-layer neural network.

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The core of all these developed approaches is the search for an error evaluation's model that could be easily and, preferably real time, computed. Most of the models proposed are just descriptive of the effect of error on machined surfaces while few try to model the manufacturing process and the sources of errors. Thanks to the ever increasing computational power of the modern workstations, it is possible to simulate, in a reliable way, not only the effect of error but the whole machining process and the machine behaviour during cutting operations, including tool deflection and vibration.

The general idea of the authors paper is to develop a reliable dynamical model of a machine tool to simulate the relative tool wok-piece quasi-static error displacement. In this case some experimental test will be needed to validate the model but, thanks to DoE analysis of numerical results in the error sources synthesis, their number is low. Two strategies for the simulation of machine tools are actually largely used. The first one is the rigid multi-body simulation which is used to calculate kinematic performances as the reachable accelerations of the axis, eventually also using visco-elastic elements to calculate the internal forces of the joints. The second strategy is the finite element method (FEM), to optimize structural parts, to perform thermal or vibrational analysis. Each of these methods is capable of describing the machine behaviour with different degree of precision and with different needs of computation and characterization time. However none of these methods is able to predict both the vibrational and static behaviour for a machine whose configuration is continuously changing due to different axes positions. This problem could be solved with the use of a more advanced approach: the multi-body flexible model that link together the machine elements using visco-elastic joints and include also the flexibility and vibratory behavior of the components thanks to the use of FEM. This possibility is actually provided by some commercial multi-body softwares, such as MSC Adams®.

The scheme for the tool-path optimization is reported in figure 1. The input data for the multi-body model are the cutting forces and the axes movement, this information is used both to evaluate the machine tool deformation due to axis acceleration and tool deflection.

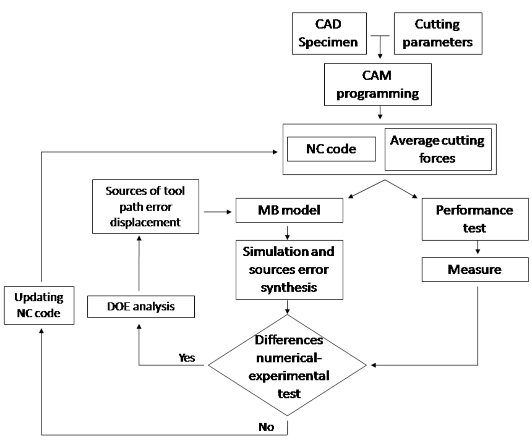


Fig. 1. Scheme of the optimization process

The machine chosen for the application of the model is a very simple three axes milling machine, mainly used for prototyping, a Modela MDX40 by Roland. The choice has been made in order to have a machine whose accuracy would be low and whose errors could be measured easily and that would be controllable using a general purpose programmable control card. For this activity the machine has been disassembled to acquire most of the geometrical dimensions and weight and to implement a change in the control of the axes. Also for this activity has been used a National Instrument PCI 7344 motion control card to control the three stepper motors instead of the original, proprietary, control. This change has allowed an easier programming of the axes movements, indeed limited by the original control. The idea is to evaluate if such correction strategy would work on a simple machine and replicate later the approach on a more complex machine. Actually the application of this strategy on a Mori Seiki NMV1500DCG 5 axes milling machine is ongoing.

2. MULTI-BODY MODEL OF THE MACHINE

The machine used for this research is depicted in figure 2, in particular it has three couple of cylindrical joints and the transmission is operated by a timing belts.

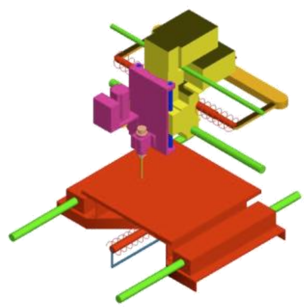


Fig. 2. Structure of the three axes milling machine

The table is able to shift in Y direction, while the Z axis is mounted on the X carriage. The kinematic chain of the milling machine is described in greater detail in the diagram of the kinematic chain of the multi-body, hereinafter referred to as integrated with the sources of error introduced, see figure 6.

As assumption the geometrical errors introduced by imperfections of the guides consider six of the seven factors commonly cited in the literature (Okafor, et al., 2000). These factors are the error of linear positioning, the error of straightness in the two orthogonal components to the axis, the three angular positioning errors associated yaw, pitch and roll of the sliding body.

2.1 Backlash in the cylindrical joints

The first source of error introduced in the multi-body model is the radial gap of each cylindrical joint, according to the specification provided by the manufacturer of the joints. By the introducing of the radial gap of the joints it is possible to evaluate the two orthogonal components positioning errors and the three angular positioning errors. The gap of the cylindrical joints has been modeled providing a virtual stiffness behaviour of the joint that is equal to zero for a displacement that is lower than the joint gap. The stiffness for displacement greater than the gap is computed using the hertz theory, the resulting function is reported in figure 3.

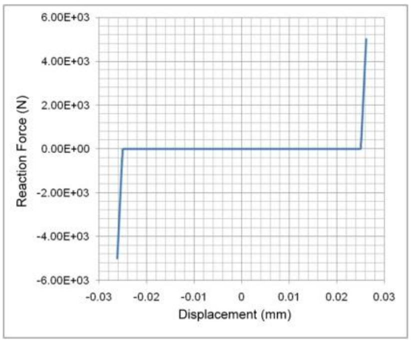


Fig. 3. Gap-stiffness function for cylindrical joint.

The effect of the joint gap when the tool holder is loaded is presented in figure 4 where is considered, to make the example clear, only the gap of the vertical axes cylindrical sliders.

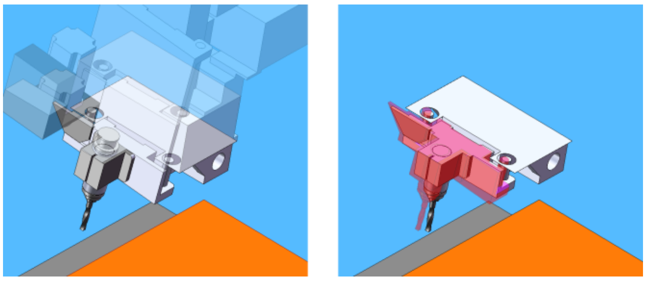


Fig. 4. Amplified roll of Z axis carriage due to the gap in cylindrical joints.

As another assumption the orthogonality axis errors are not considered and this fact simplifies the model in its construction providing an advantage over the possible default of the model. In fact, as shown in the UNI ISO 230-4, the orthogonality axis error in executing a circular trajectory transforms the nominal circular trajectory into an ellipse with principal axes arranged at 45°. Therefore the orthogonality axis error can be considered already known in terms of expected results.

2.2 *Linear motion errors*

The linear positioning errors have their origin in the transmission mechanics system and numerical control, so two aspects must be taken into account for this three axes milling machine. The first source of the linear positioning error is the elastic compliance of the belt never used in industrial machine tools and second, the milling machine has no feed-back control in the axis movement. While the loss of one or more steps of stepping motor introduces a small linear positioning error of about 2 μm / step, the backlash in the pulley-shaft coupling and the hysteresis phenomena into timing belt cause a gap in the linear positioning of the axis. Therefore it is evident that the linear positioning error has simple implementation in the model through the introduction of a gap in the kinematic chain of mechanical transmission, but it requires a more accurate calibration, due to uncertainty about the origin of the phenomenon.

The multi-body model has been assembled using MSC Adams® and in his construction the flexibility of belt and tool are introduced as another sources of tool path error, while the machine structure is firstly considered rigid. Depending on the position of the axis the stiffness of the belt transmission system varies as changes the length of the branches. In particular, the stiffness of the branch from the driving pulley to the sliding body is maximum at the end of travel in correspondence of the drive pulley, and minimum in the other end. These characteristic is opposite for the other branch stiffness. The overall stiffness of transmission belt system is given by the sum of the stiffness of the two branch, as pictured in figure 5.

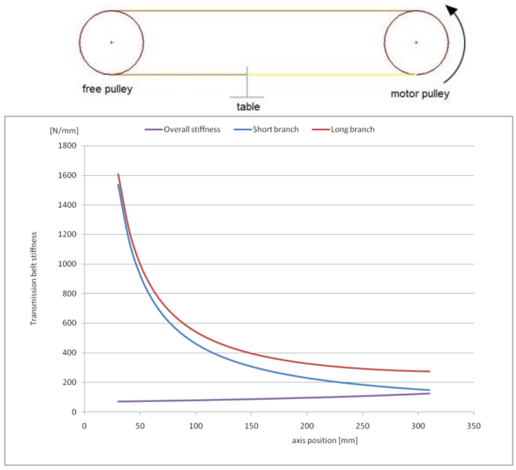


Fig. 5. Scheme of the stiffness of the timing belt.

Due to the low cutting forces and the low stiffness of the actuators (i.e. timing belt) respect to the machine structure it could be presumed that the structure stiffness would play a minor role in the tooltip positioning error. For this reason only the deformation of the component with the lowest stiffness has been considered in this model: the end mill. This solution allows a faster and easier computation of the simulated tool-path. For more performing machines recent studies has been carried out to create a fully flexible multi-body models, mainly using "reduced" FEM model of the components thanks to the adoption of the super-element strategy. The super-element could be created using commercial FEM code and it reduce the behaviour of the components to the interface nodes only, the most common formulations are the Craig-Bampton, 1968, or the Tönshoff et al., 2002, one. For such models the key issue is the characterization of the joints, while using a simple three axes machine this approach could be solved more efficiently as proposed.

2.1 *Kinematic chain of the model*

The kinematic chain of the multi-body model is represented in figure 6. This scheme summarize the each sources of error introduced in tool path simulation. In order to synthesize the total error from each sources of error some measuring points are introduced downstream of each source itself in the multi-body model. For example, the measure between the red point and blue represents only the error contribution due to flexibility of the tool and the belts of Y and Z axis.

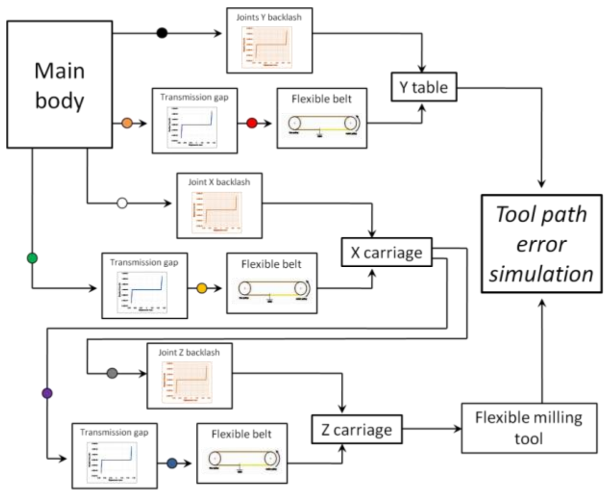


Fig. 6. Scheme of the kinematic chain of the multi-body model.

3. VALIDATION OF THE MODEL

The test of the model have been carried out using a simple circular tool path, chosen because it allows an easy and high precision measurement of the differences between the real tool path respect to the designed one, using a roundness meter (a Taylor Hobson roundness meter, equipped with a National Instrument acquisition card, NI-9205, with simultaneous sampling). Five circular grooves shown in figure 7 with different diameters have been machined in down and up milling and then measured.

Fig. 7. Test piece.

The simulation results for counterclockwise tool-path corresponding to down-milling and for clockwise tool-path corresponding to up-milling show both a good accordance between the simulated path and the real one, as presented in figure 8. Better accordance is given for finishing conditions where cutting force is lower and flexibility of the machine tool structure can be neglected. The most relevant difference between the simulated and real tool path is the presence of the roughness due to tool and machine tool structure vibrations that our model is not able to predict. The first set of experimental tests has been used for the tuning of transmission gap values and cylindrical joint gap. These values are the ones that minimize the difference between the real tool-path and the simulated one. These constants have been found for a configuration and, to prove the robustness of the approach, other configurations have been tested and compared with experimental data. The final gap have no more than a 20% difference respect to the value provided by the joint manufacturer (25 µm). The most visible effect is the rapid shift of the radial position due to the change of the axis direction that are responsible for a rapid change in the belt stiffness.

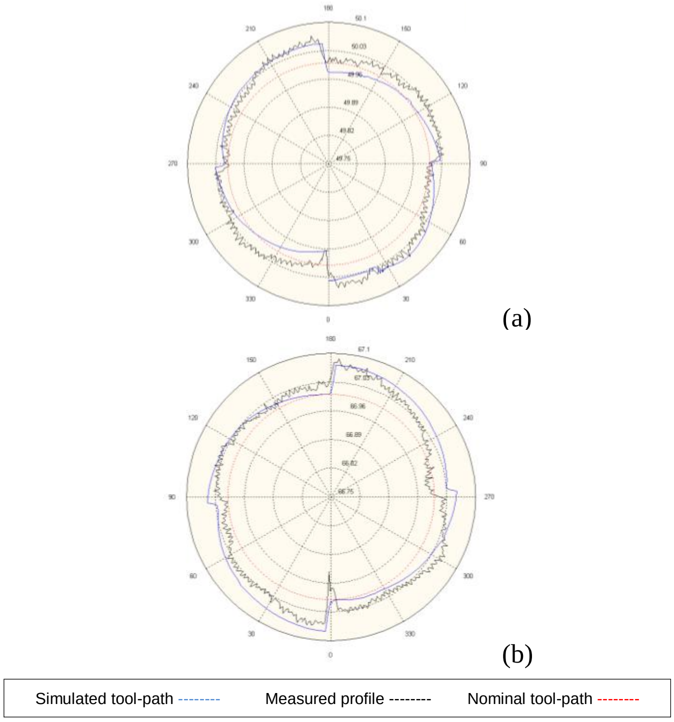
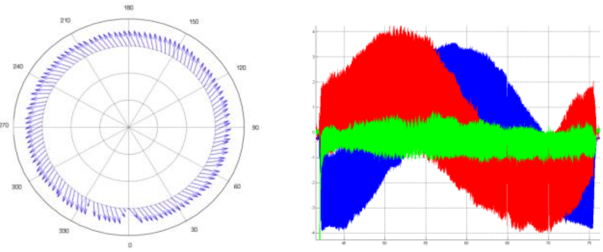


Fig. 8. Simulated clockwise tool-path and experimental test data in up-milling (a) and counterclockwise, down-milling (b).

For the cutting forces has been developed an analytical model to predict module and directions of the forces given the geometrical, material and process parameters. This model has been validated thanks to experimental tests using a Kistler three axial load cell: the forces have been measured for a given tool path and their graphical representation is reported in figure 9; the modulus and the direction respect to the feed vector could be assumed nearly constant.



(a) (b)

Fig. 9. Cutting force acquired using a piezoelectric cell, polar (a) and timeline (b) representations.

Once the simulation model has been validated a sensitivity analysis has been performed in order to evaluate the influence of the joint gaps and transmission gaps on the circularity error of the machined pocket. A DoE considering as factors the flexible tool and the gap on the three axis has been defined. The levels of the factors are if each source of error is considered or not in the simulation model. The model used include as default the flexibility of the timing belt and the cutting and inertia forces. The test plan is reported in Table 1.

Table 1. DoE of the simulated model.

Simulation measures	Flexible Tool *(flex)*	X axis gap *(gapX)*	Y axis gap *(gapY)*	Z axis gap *(gapZ)*	Circularity error *(μm)*
1	1	1	1	1	106
2	1	0	0	1	69
3	1	0	1	0	90
4	1	1	0	0	65
5	0	0	1	1	73
6	0	1	0	1	70
7	0	1	1	0	78
8	0	0	0	0	56

The regression model obtained is the following (1), from which is possible to highlight that the most relevant factors are the presence of a gap on the Y axis and the deformation of the tool.

$$\begin{aligned} error &= 79{,}9 + 5{,}2 * flex + 2{,}2 * gapX + 9{,}4 * gapY + 2{,}5 * gapZ + 2{,}7 * flex * gapX \\ &+ 6{,}2 * flex * gapY + 0{,}7 * flex * gapZ \end{aligned} \quad (1)$$

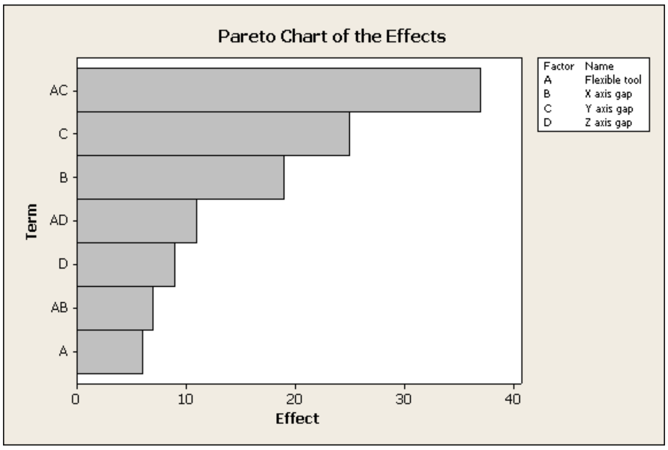


Fig.8 Pareto charts of the effects of the four DoE parameters.

4. CONCLUSIONS

This paper proposes an approach for the simulation of the behaviour of a machine tool subject to cutting and inertia forces that enable the user to virtually predict the tolerance and geometrical errors of the machined surface. The simulation based on flexible-rigid multi-body has proved an high reliability of the results, although the joint characterization is still an issue for the more complex geometry like five-axes machine tool. The optimization approach used has proven to be able to correct efficiently the geometrical errors but it is unable to reduce the roughness of the profile due both vibration and tool cutting mechanics. More complex optimization model that could predict not only the quasi-static but also the dynamic behaviour of a machine could be implemented considering the flexibility of every machine part, in this case the optimization would take into account also other process parameters such as the feed and spindle speed.

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