SHORT LITERATURE REVIEW ON THE OPTIMIZATION OF THE FIVE-AXIS CNC MACHINES

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***Abstract*—**This paper is a the result of a short literature review on the optimization of the five-axis Computer Numerically Controlled (CNC) machine, a first study conducted in a wider research that will be further developed in this field. After a short presentation of these machine tools, are presented some approaches regarding the optimization and virtual modeling of the multi-axis machines.

***Keywords*—**optimization, modeling, five-axis CNC machine

I. INTRODUCTION

IN order to achieve the productivity growth in the current trend of the integrative engineering, a series of researches are focused on the development and analysis of the methods for decreasing the time required for the transition from computer modeling of the surface shape to the machining it, in condition of maintaining or improving the quality of the surface finish. The five-axis Computer Numerically Controlled (CNC) machines have many advantages in the machining of the complex sculptured surfaces, such as the reduction of the machining time and improving the surface finish.

In this context, the generation and optimization of the trajectory for the multi-axis machines, in this case for the five-axis machines, is an interest research field in recent years. Offering greater flexibility and a high potential to increase the efficiency of machining, because of the additional number of degrees of freedom and, implicitly, because of the opportunities of the tool orientation relative to the workpiece, in recent literature were developed and presented a large number of tool path planning methods [1] [2].

II. SHORT PRESENTATION OF THE FIVE-AXIS CNC MACHINES

The five-axis milling machines are classified according to the combination and order of the linear (T) and rotational (R) axes. The selection of certain variant is very important because not every machine can perform any task. On the contrary, the same tool path executed on different CNC machines produce noticeably different results [2]. The diversity and complexity of the configurations have imposed their standardization, the direction and the sense of axes being defined by EIA RS-267-A, NAS-938 and ISO 841-1974 [3], revised in 2001.

From the multitude of possible combinations, three are commonly used to configure machines in five axes, namely:

1) *RRTTT: a tilt rotary table mounted on three linear axes usually referred as a the tilt-rotary type 5-axis machine*
2) *TTTRR: three linear axes with the cutter oriented by two rotary axes, commonly called a wrist type or Euler type 5-axis machine*
3) *RTTTR: a rotary table mounted on three linear axes and a single rotary axis for the tool [4].*

Each of these configurations has certain advantages and disadvantages. Thus, wrist-type machines, that are the most commonly used for surface machining, are the simplest to the program, can be used for the machining very large workpieces, but tend to be less rigid than other configurations. Tilt-rotary table type machines excel at five-axis machining and tend to be stiffer than other configurations, but they are more prone to installation errors and can’t process large workpieces [2].

The performance of a machine tool is given by the accuracy; that is affected by the geometric errors, caused by the mechanical-geometrical imperfections, misalignments, and wear of the linkages and elements. Also, the dimensions accuracy of the workpiece depends on the positional accuracy of cutting tool relative to the workpiece [5].

There are 41 known geometric errors for the five-axis CNC machines. In a study it is proposed a method to measure, modeling and compensate these errors, represented by error motion twists, the direct and inverse kinematics being modeled by using the screw theory [6].

In some studies the kinematic structures of the machining centers are assimilated with the collaborative robots structures (one tool robot and one table robot, assembled on a common platform), and mathematical modeling of the position and the orientation of the tool relative to the workpiece and the workpiece relative to the tool is made using the direct method. In total, the two robots can make motions on 12 axes, six linear and six rotational. By canceling certain motions, can be obtained the kinematic structures of different types of machining centers [7].

III. Optimization of the Five-Axis CNC Machines

In the current context of products and processes 'green', environmentally friendly and in the light of some studies showing that, in some flexible manufacturing systems, the average power used to processing is less than half of the available power, and only 60% of the total time is used for production, has occurred the necessity to some approaches in the sense of the energy efficiency for machinery and processes in the flexible manufacturing systems. Among the strategies developed to achieve this goal is a redefining the cutting strategy and tool path planning [8], [9].

The general optimization problem requires finding those sets of positions and orientations of the tool and the machine wherewith the desired surface is produced in a minimal time and with a minimal error.

To improve the machining processes of free-form surfaces in the literature are mainly presented three approaches: different techniques to smooth the tool path implemented in the CNC machine; improving the computer-aided manufacturing (CAM) algorithms to generate better tool paths; new tool path formats to avoid the CAM discretizations. Two key factors for improve the quality and productivity are considered managing the tool path geometry, and the kinematical parameters of the machine tool. In this context, was developed a new method, a unified method, the direct trajectory interpolation on the surface (DTIS) method, that compute the trajectory directly on the surface to be machined avoiding CAM approximations and producing a smoother trajectory. Through experimental applications of this new method was proved that it allows obtaining a higher productivity and a better surface quality [10].

In a research is proposed an efficient computation approach, that uses a pseudo-jerk for approximate the real jerk and for obtaining smoothing trajectory. Through solving a convex optimization problem, the efficiency of the process is obtained by using ordinary gradient-based optimization techniques, the optimal numerical solution being uniqueness. Through solving a convex optimization problem, the efficiency of the process is obtained by using ordinary gradient-based optimization techniques, the optimal numerical solution being uniqueness [11].

Some ongoing research trying to develop new strategies for positioning the tool, that put the tool profile closer to the projected surface and thus reduce the need for subsequent finishing operations. Also, are searching the fastest techniques for trajectory simulation and toolpath verification to help detect and prevent the roughness defects and the interferences. [2].

There are various methods for the management of the local interferences in a five-axis milling machine. One of these proposes a positioning strategy combined with the balancing of the transversal cutting force. Application of this method leads to the stabilization of the cutter and a net improvement of its dynamic behavior, and, finally, to a significantly higher quality of the milled surface [12].

In some experimental studies were investigations done and was demonstrated that varying the tool orientation in five-axis micro-milling of brass using ball-end mills reduces rubbing of the material and improves the final surface quality. A tool inclination angle of 15° can improve the surface roughness at the bottom of the grooves by 35 % compared to the case of cutting with a zero tool inclination angle, and can reduce by half the static cutting force values [13].

The accuracy and efficiency of the five-axis machining of free-form surfaces can be enhanced through elimination of the “unnecessary” actuation of the machine rotary axes. For obtain it, has been addressed the problem of determining the rotary-axis inputs to 5-axis CNC machines, so as to minimize variations of relative tool/workpiece orientation under the constraint of a fixed cutting speed with a ball-end tool. In this context, some researchers propose an optimal tool orientation control by using an inverse kinematics solution [14].

In another study, to reduce the machining time and to gain in productivity, is proposed a method which provides to be adopted for a workpiece those setups that minimize the distances covered by the machine axes, relying on the analysis of the machine’s kinematic behavior [15].

Makhanov, in [1], [16]- [18], has extensively studied tool path optimization for a five-axis CNC milling machine and presents some algorithms for optimization, verified by numerical experiments as well as by practical machining. These algorithms rely on the variational grid generation; a new modification of the space filling curves techniques; construction of the vector fields composed of optimal cutting directions; the optimization of a set of feasible rotations; a least-square optimization regarding a setup of the machine. The first three are designed to optimize the tool positions and orientations and are based on adaptable geometrical structures. The last two are based on the adjustment of the machine kinematics rather than finding the optimum given fixed kinematics equations. Applying of the fourth algorithm leads to a substantial increase in the accuracy ranging from 10 to 80% and applying of the fifth algorithm in many presented cases show an accuracy increased up to 99%. These results show the efficiency of the proposed optimization methods [16] [17].

Later, after a survey on the adaptable geometric patterns for five-axis CNC machining (the navigated paths, the space-filling curves, the cluster-based or region-based methods, the curvilinear grids), Makhanov [18] says that these constitute a promising trend in the modern tool path generation. The future intelligent adaptive tool path generation should include a combined approach of the quality criteria with the technological parameters and with the machine kinematics.

To reduce the machining time has been proposed a new method for generation of vector field-aligned tool paths for five-axis machining, using a curvilinear tool path aligned with the direction of the maximum removal rate. By applying this method was obtained up to 70 % decrease in the machining time, a considerable reduction of the tool path length and the waviness, while the kinematic error and the roughness of the workpiece remain practically unchanged [19].

The most researchers study the geometric aspects (optimal tool path, optimal tool orientation) separately by the dynamic aspects. Only a few have a combined approach of geometric and dynamic aspects.

To achieve the optimal performance of the CNC machines is a need to be fully utilized their dynamic capabilities. In many studies is approached an optimization of the tool path or tool orientation with different dynamic constraints, such as the velocity stability, cutting forces, feed rates, and torque of a 5-axis CNC machine.

Usually, the system dynamics is simplified, or hardware capability constraints are developed without higher order states. A new research introduces a heuristic trajectory optimization algorithm (feed rate optimization algorithm) that supports the incorporation of constraints with higher order dynamic states (jerk, jounce, and derivative of jounce), without sacrificing the computational efficiency [20].

IV. The Finite Element Method

The finite element method is a numerical analysis method applied in all fields of engineering, providing an approximate solution to a given problem. The finite element method applies particularly where an analytical solution is difficult to obtain, especially when the conditions on borders are not uniform.

The finite element method is applied in several stages, namely: pre-processing, solving the problem, and post-processing. To perform a finite element analysis of a structure first has to be developed the calculating model of the structure. Elaboration of a correct and efficient computational model depends on several factors and must meet certain conditions. Since there are not general algorithms and methods to ensure the development of a unique model that approximates the structure with a pre-established and known error, the important factors in the development of the model are intuition, imagination and previous experience of those who do the modeling. Thus, it is possible to be developed more models for one structure, all correct but with different performances.

In recent years had been done several types of research regarding the application of the modeling methods with a finite element of the machining processes in order to develop an ideal model, efficient and precise, able to predict the machining performances without an experimental machining. The most cutting models using finite element method can be classified into two categories: the chip formation cutting model, and the steady-state cutting model. More recently, with the increasing demand for ultra-precise machining, studies have been conducted on micro cutting using molecular dynamics simulation [2].

In the present, the finite element modeling is included in some software applications and is used for static and dynamic analysis of a machine tool. By using the finite element modeling of a CNC machine on the software ANSYS, was obtained an improving of the machine structure, a better-working accuracy and an important theoretical basis for optimization [21].

V. Modeling of the Five-Axis CNC Machines

The modeling and simulation of the five-axis machining process can be used for the selection of the proper process parameters and leads to the improving of the productivity and the quality.

The CNC machines are programmed to generate a required tool trajectory using a special command program called G-code, which is a standard for the CNC machines industry. G-code program can be written manually for simple parts. CAM software typically produces G-code program, directly from CAD models, in two stages. First, the tool paths are generated, consisting of the generic cutter locations data (CLDATA) that are a list of the tool positions in the coordinate system of the workpiece. These cutter locations must then be converted into G-code programs using a post-processor specific to the CNC machines. There are many CAM software compatible with CNC five-axis machines, but the available features of these systems vary greatly, so is very important to choose the proper one. More sophisticated CAM packages can do inclined millings, where the tool is inclined at an angle to the surface normal, and the tooltip is placed in contact with the surface [2].

In a study is developed a procedure for extraction of milling conditions from cutter location data and a practical method for integration of the model of a five-axis CNC machine with the CAD/CAM systems. Then, using this approach is demonstrated through example, the simulation of the milling forces in a cycle and the scheduling of the feed rate to shorten the cycle time [22].

Using the finite element analysis of ANSYS package, the virtual design and kinematics simulation in SolidWorks and ADAMS, for a combined CNC machine tool of turning and grinding, has been obtained a simplification of the design process, a shorter period for development and an improving of the designing quality

[23].

Also, using the ADAMS software, in a study has been constructed a virtual prototype of a five-axis CNC machine tool, has been simulated the machining process and has been carried out the dynamic analysis. It was proved that by improving the structure of the column can effectively raise the working accuracy [24]. The results of another study prove that simulation analysis based on a rigid-flexible coupling model show more accurate the dynamics characteristics of the machine tool [25].

The simulation of a trajectory following on given path has been done in a study using the RobWork software package, which gives the possibility of mapping the process of cutting through the animation and control of the process parameters [26].

For an efficient machining, has to be done a proper selection of the machine tools and the scheduling the parts on production floors. In choosing them, an important role is the prediction of machining cycle times for CNC machining centers. Studies in this sense show that is possible to predict the part machining cycle times within 95% accuracy by extracting the trajectory profiling parameters and sharp corner contouring strategies of the commercial CNC machine, via a “virtual CNC” [27].

VI. Conclusion

After a short literature review, we can conclude that the optimization of the five-axis CNC machine is a wide research field and includes multiple criteria and different approaches. This work will be further thorough and developed to find the best approach for modeling and to optimize a five-axis CNC machine in ADAMS software application.

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