43. JUPITER konferencija
Beograd 2022
30. simpozijum
CAD/CAM

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STATE OF THE ART IN THE FIELD OF FORCE PREDICTION IN BALL END MILLING

Abstract: Simulating the process of NC milling is of fundamental importance in computer aided design (CAD) and computer aided manufacturing (CAM). Cutting force prediction is very important to optimize machining parameters and monitor machining state. In order to predict cutting force of surface machining with ball end mill, contact state between cutter and workpiece are studied. The resulting surface quality after machining with ball end cutter is of superior importance because finish milling is often the last process step determining the functional performance of a component. In this paper is presented the state of the art in the field of force prediction in ball end milling and advantages of different methods for determining the cutter-workpiece engagement.

Key words: Cutting force, ball-end milling, free-form surfaces, CAD/CAM, cutter-workpiece engagement.

1. INTRODUCTION

In order to produce the parts with free-form surfaces in an optimum manner in terms of production cycle time, cost and product quality, the machining process of free-form surfaces needs to be simulated faster and more accurately in advance. Ball end milling is mainly used for finishing operations and manufacturing of complex parts. Besides high geometric accuracy and low surface roughness, a compressive residual stress state is often required, e.g. in aerospace parts. Disadvantages of using rounded cutting edges are increased forces because of additional ploughing as well as a possible burr formation. [1-2].

The evident feature of ball end milling for sculptured surface is that the contact condition between the tool and workpiece varies along the tool path. In sculpture surface machining, the cutter/workpiece engagement region does vary along the cutter path and in general, unless some specific and very simple workpiece geometry is machined, it is difficult to find an exact analytical representation for the engagement region. It changes cutter-workpiece engagement (CWE), which defines the area where cutter and workpiece interact to generate cutting force. Beside force calculation prediction, chip load is based on CWE therefore the output of the engagement model is very critical. Chip load and force calculations are based on the cutter/workpiece engagements; therefore the output of the engagement model is very critical. In order to model the process mechanics and dynamics accurately, it is important to have a precise geometric representation of the CWE surface. [3-5]

The researches for CWE under different cutting conditions are mainly divided into three types: solid modeling, discrete representation, and analytical methods, and this paper is divided in sections by these methods and explaining what are advantages and disadvantages of every method studied by different scientists. After these sections there will be presented different examples for determining the cutting forces. Through comparison studies, the model predictions are verified by the corresponding results obtained via different modeling approaches in CAD environment.

2. SOLID MODELING APPROACH

Solid modeling approach or solid modeling techniques mainly are used to model three-dimensional objects and were designed in the 1960s. Most common techniques in the solid modeling approach are: boundary representation (B-Rep)(Fig 2.1.a) and constructive solid geometry (CSG) (Fig 2.1.b).

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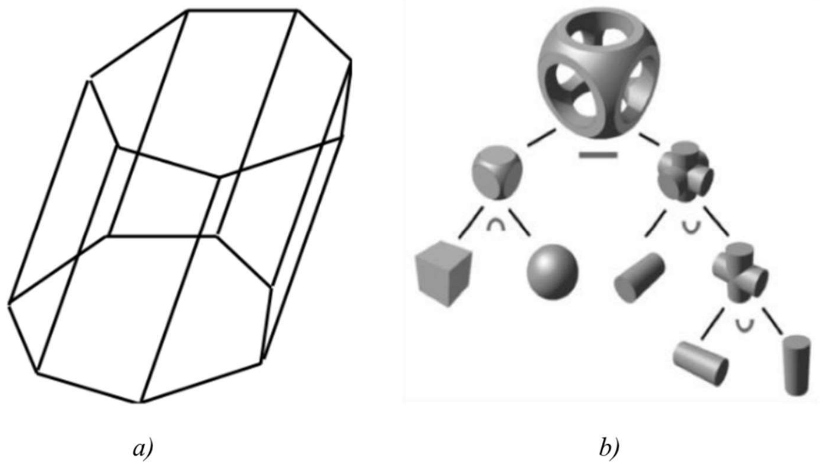
B-Rep is a method of describing solid object like it is said in the name of method (Rep is short for representation), by their boundaries. There are many types of boundaries, but the one that is used in this paper are free-form surfaces which could be described in numerous mathematical ways. Some of the most common mathematical descriptions of free-form surfaces are Bézier curves, B-spline curves and non-uniform rational B-Splines also known as NURBS.

Imani and Elbestawi [6] B-rep solid modeling techniques are used to deal with geometric modeling issues encountered in ball-end milling simulation. They used precise B-rep model of the cutter swept volume that is developed using advanced sweeping techniques and developed a simulation system for modeling semi-finishing and finishing operations. B-rep model of the part with free-form surfaces is accurately and efficiently updated by the system.

Sadeghi [7] et al. presented a system for geometric and physical simulation of the ball-end milling process using solid modeling. They have realized that all the research works in this field is done used either geometric or physical modeling of ball-end milling process and set a challenge to develop a method using an integration of these two methods, which could be applied to a wide range of tool and cut geometries. The cutting edge and updated part geometry are modeled using a commercially available geometric modeler (ACIS). By using this method, researchers managed to develop an approach for prediction of the static cutting forces, the dynamic forces and tool deflection in machining of die surfaces with ball-end mills.



a) *b)*

Figure 2.1. *Representaton of most common techniques in the solid moddeling approach*

Lazoglu et al. [8] did their work in making new approach for predicting cutting forces in five-axis machining of parts with complex free form surfaces. Advantages of developed model are numerous: it provides an efficient and accurate solution for extracting the information on contact region at cutter location (CL) points from the in-process workpiece and it allows especially for multi-stage process simulations including roughing, semi-finishing and finishing. Before them, scientists have developed various approaches to improve the performance of five-axis machining process. Sorby et al. [9] proposed an empirical method for selection of cutting tool and machining data for flank milling based cutting tool life and cutting forces. Lauwers et al. [10] developed a five-axis tool path generation algorithm based on faceted or tessellated models. Becze et al. [11] introduced an analytical chip load model for five-axis high-speed milling. Biermann et al. [12] showed effects of workpiece vibrations on five-axis milling of turbine blades. Budak et al. [13] presented models for milling stability analysis where the process geometry is extracted using a semi-analytical engagement method. Ferry and Altintas [14] developed a semi-discrete solid modeler based simulation system for five-axis flank milling.

Yang et al. [15] proposed a solid modeling-based method to extract CWE for multi-axis milling. In addition too improve efficiency they extracted CWE based on the removal volume, rather than the in-process workpiece. Conducted numerical simulations show that the method is reliable and efficient by comparing with existing approach.

Hengyuan et al. [16] proposed a new method for high efficiency calculation of CWE in five-axis milling based on the distance field and envelope theory. In the geometry modeling and milling simulation, workpiece surfaces are modeled using sampled distance fields stored in a well-designed octree data structure for efficient memory usage. The inverted trajectory method is used to calculate the tool swept volume, which is subtracted from the in-process workpiece by performing three-stage intersection Boolean operation.

After comparing the CWE diagrams calculated by newly developed method at specific CL points with the B-rep based method, researcher came to conclusion that the proposed method is faster than the B-rep method with almost the same accuracy except on some independent sharp corners. Another advantage of this method is that the CWE diagrams of over 12,000 CL points can be calculated in several minutes, which makes it practical for industrial applications.

Yip-Hoi et al. [17] presented a solid modeling based solution for calculating CWE geometry when multiple setups and tool changes are considered. The cutter engagement feature (ceF) which represents the characterization of the cutter/workpiece intersection over a single revolution of the cutter has been identified as a representation of the CWE at each feed step of the cutter during $2\frac{1}{2}$ D end milling.

The direct Boolean subtraction approach is an exact and analytical approach. It directly performs the Boolean subtraction operation between a solid model and the volume swept by a cutter between two adjacent tool positions. Although this approach can provide accurate verification and error assessment, the computation cost is known to grow too much for a numerous tool-paths. [5]

3. DISCRETE REPRESENTATION

Main advantage of discrete approaches is that they are computationally simpler than the solid modeling approach. Typically, discrete methods require intersection calculations between simple geometric primitives, allowing simple and robust analytical or algebraic solutions. This simplicity provides robust behavior and also increases the computational efficiency.

Discrete representation of the geometry may result in the loss of geometric accuracy. However, if the simulation parameters are selected properly, considering both workpiece and tool path tolerances, the error introduced by the discrete representation may be kept in an acceptable level.

There are several discrete methods used for the representation of the in-process workpiece such as Octree, Voxel, ray representation and Depth buffer (Dexel) approaches.

In Octree and Voxel approach, workpiece is modeled as volume cells (Voxels), for instance cubes for the Octree data structure. Octree method is based on the divide-and-conquer principle that recursively subdivides a cube into octants up to specified resolution. Coordinates of each vertex (node) in a voxel is stored and by checking the inner–outer nodes stock workpiece is obtained. During NC simulation tool swept volume between two CL points is subtracted from the stock workpiece and machined workpiece is obtained. This method is simple and fast, however, main drawback is the excessive memory requirements (especially at high resolutions) due to the large amount of data stored.

The most popular and commonly used Depth Buffer scheme in the literature and in the CAM software is Z-Buffer method. Z-buffer method is usually referred as Z-map method. In conventional Z-map method, workpiece is represented as the intersection points of the Z direction vectors (ZDV) with the workpiece surface on a 2D grid of ZDVs. These intersection points are also upmost part of the workpiece surface where only one intersection of the workpiece with a ZDV is permitted. [5]

Roth et al. [18] presented graphical representation of the tool movements to determine the in-process chip geometry and tool edge contact length using an adaptive and local depth buffer. In their word this method is improved in the way to include the effects of complex tool geometry.

Jian Guang Li et al. [19] presented an improvement of the geometric simulation efficiency on three-axis milling process using hybrid discrete representation method. Used method is a combination of advantages both of the Z-Map and quadtree in simulation model representation. Researchers came to conclusion that this method can improve simulation efficiency significantly compared to single quadtree.

Taner et al. [20] published research about comparison of solid model and three-orthogonal dexelfield methods for cutter-workpiece engagement calculations in three- and five-axis virtual milling. The first method is a discrete model which uses three-orthogonal dexelfield, and the second method is a solid modeler-based model using Parasolid boundary representation kernel. They compared both CWE calculation methods in terms of speed, accuracy and performance for three- and five-axis milling of ball-end and flat-end mill tools.

Boz et al. [21] compared two methods for CWE calculations in three- and five-axis virtual milling. First method they used is a a discrete model which uses three-orthogonal dexelfield and the second method is a solid modeler-based model using Parasolid boundary representation kernel.

Popovic et al [22] identified cutting coefficients by applying the orthogonal cutting mechanics, which are used in the cutting forces and torque prediction. In part of their research they used an unified cutting force model for turning, boring, drilling and milling operations developed by Kaymakci et al. [23].

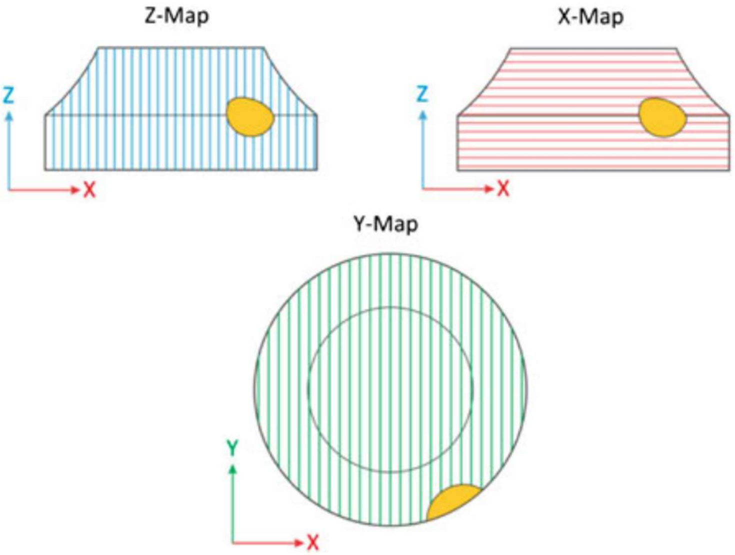


Figure 3.1. *Illustration of three-orthogonal dexelfield [21]*

Theegarten et al. [24] presented an efficient method for calculating discrete engagement maps for five-axis milling operations. Used method is based on the tri-dexel volumetric model, which is commonly used in Computer Aided and Virtual manufacturing for validation and verification of NC programs. Presented approach sometimes suffers due to the errors attributed to the discrete simulation, the existing problems can be mathematically analyzed and reduced.

Wang et al. [25] solid-discrete-based method is used to precisely and efficiently identify the CWE between the end mill and the surface being machined.

In order to realize fast and sufficient precise CWE calculation for five-axis milling, Ma et al. [26] presented an efficient approach based on the distance field and envelope theory is proposed in this paper.

Nie [27] proposed several CWE extraction methods based on vector models, where the in-process workpiece is represented by a set of uniformly distributed line segments along z-axis.

4. ANALYTICAL METHOD

In literature could be found that first analytical positioning was described initially in 1979 [28]. Analytical methods based on geometric analysis or mechanistic force models have also been employed extensively. This method generates the CWE maps by identifying the geometry intersection between the cutter and the workpiece. Bezier, B-spline, and nonuniform rational basis spline (NURBS) curves or surfaces are often used to represent the geometries of the cutter and the workpiece. Mladenovic et al. [29] presented that each point on the surface is calculated using the corresponding formulas as a function of two parameters, u and v. The advantage of analytical method lies in its good accuracy and time saving when the concerned workpiece geometry is relatively simple. [15] These approaches aim to either deal with cutter positioning and/or tool path selection problems or cutting condition value optimization by examining the developed cutting forces. As mentioned, the developed algorithms can easily be used in various optimization schemes and are fairly accurate. On the other hand, they are usually computationally expensive and despite the rigorous mathematical background, they still involve several simplifications about the developed cutting phenomena. [5]

Bailey et al. [30] analytically carried out this calculation by determining the intersection between the NURBS defined cutting edge and the part's local surface topology, defined as the surfaces generated by previous tool paths in the vicinity of the current tool position. Ozturk and Lazoglu [1] used the cutter location (CL) points to yield the instantaneous CWE maps in the machining of monotonic free-form surface. Recently, Budak et al. [13] proposed alternative analytical models to compute the process geometry, such as depth of cut, lead, and tilt angles, together with CWE maps for five-axis milling.

Zhu et al. [31] used a cutting edge element moving method to calculate instantaneous undeformed chip thickness for general cutter five-axis machining. The cutting edge element is involved in cutting when it is under the workpiece surface and outside the tool envelop surface. Zhang et al. [32] determined the boundary of CWE by intersecting the workpiece surface and the cutter geometry, and established the analytic model of entry angel and exit angle to realize the cutting force prediction in five-axis flank milling of sculptured surfaces. Zhu and Zhang [33] proposed instantaneous milling force per tooth for the three-axis horizontal non-grooving milling of ball end mill. The CWE was divided into different milling areas, and the corresponding z-axial boundary analytical expression was derived.

Guo et al. [34] developed a force prediction model for five-axis flat end milling of free-form surface base on a new analytical CWE model. The experiment and simulations of five-axis milling of free-form surface show that the CWE obtained from analytical method matches with that of experiment; a slight error compared with solid modeling method, and the relative area error is within 1.2%.

Wei et al. [35] proposed a new analytic method of CWE and in-cut cutting edge (ICCE) for ball end milling of sculptured surface and established the prediction model of milling force. The CWE is obtained by spatial surfaces intersection in an auxiliary cutter coordinate system. Then space transformation is used to derive analytic algorithms of CWE in cutter coordinate system. Researchers came to conclusion that the simulation of the CWE and the ICCE, the developed analytic model is consistent well with the results of the solid modeling method based on Boolean operation.

Xi et al. [36] used an analytical method based on arc-surface intersection to calculate CWE based on arc-surface intersection method. In this paper it is proven that the proposed method is a modification of ASIM (arc-surface intersection method), an analytical method can achieve the required accuracy. If there is need for a larger number of CL points to be included, additional work should be done to optimize the C++ program to enhance the computing speed.

5. THE PREDICTION MODEL OF CUTTING FORCE

According to the Armarego oblique angle microelement cutting force model [37], the cutting force of the microedge involved in CWE could be expressed as follows:

$$\begin{aligned} dF_r &= K_{rc}t_n db + K_{re}ds \\ dF_a &= K_{ac}t_n db + K_{ae}ds \\ dF_t &= K_{tc}t_n db + K_{te}ds \end{aligned} \tag{1}$$

where dF_r, dF_a and dF_t are the radial, axial, and tangential forces of the microedge cutting edge; K_{rc}, K_{ac} and K_{tc} are the shear coefficients; K_{re}, K_{ae} and K_{te} are the blade force coefficients; tn is the thickness of undeformed chip; db is the projection width of the microedge on the generatrix; and ds is the projection length of the microedge on the generatrix.

The width db could be expressed by microaxial position angle $d\theta_T$ and ball end mill radius R.

$$db = Rd\theta_T \tag{2}$$

The length ds could be solved by the arc length differential formula.

$$ds = \sqrt{x'^2_T(\theta_T) + y'^2_T(\theta_T) + z'^2_T(\theta_T)} \cdot d\theta_T = R\sqrt{1 + \cos^4\theta_T \tan^2\beta_G} \cdot d\theta_T. \tag{3}$$

The thickness t_n is a key parameter in the bevel cutting model, which is the projection of feed per tooth in the normal direction of the sphere [38]. The tool feed direction is consistent with the X_M-axis of IMCS.

According to Duan et al. [39] and based on conventional assumption that the cutting force is proportional to the undeformed chip thickness, basic elemental cutting force model of the cutting edge element along radial, tangential, and axial direction under coordinate system of cutting edge element could be given as:

$$\begin{aligned} df_r &= K_r(h)h_j(\varphi_j, z)db(z), \\ df_t &= K_t(h)h_j(\varphi_j, z)db(z), \\ df_a &= K_a(h)h_j(\varphi_j, z)db(z). \end{aligned} \tag{4}$$

where K_r, K_t and K_a are respectively cutting force coefficients of cutting edge element along radial, tangential and axial direction, and obtained from calibration experiments which will be given in Section 4.2; $h_j(\varphi_j, z)$ is thickness of undeformed chip cut by j tooth at level z when axial immersion angle is φ_j. Figure 5.1. shows the force diagram of elemental cutting edge and transform relation between CSH and CSL.

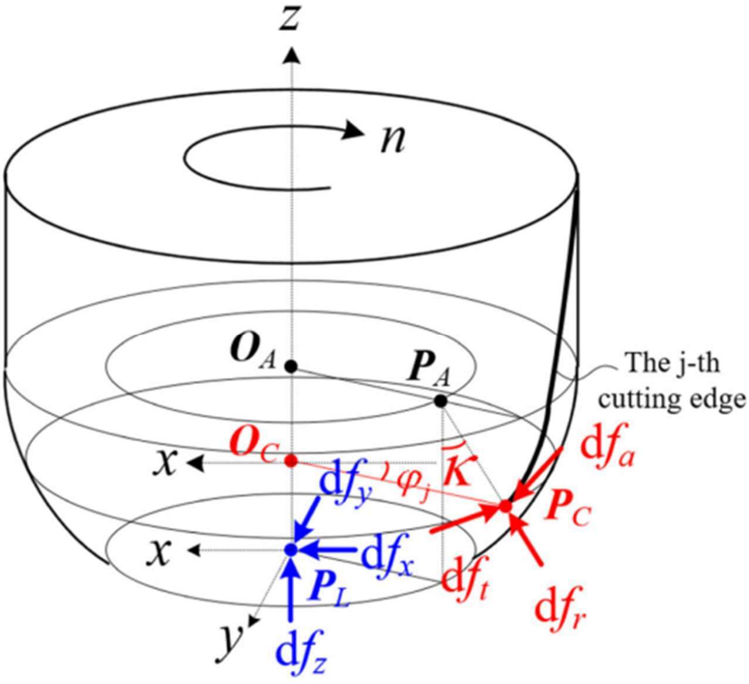


Figure 5.1. *Force diagram of cutting edge element and transform relation between CSH and CSL [39]*

Duan et al. [39] cutting force coefficients calibration experiments are conducted with the same workpiece material and cutting tool as the following verification experiments. Detailed parameters of experimental setup are shown in Table 2.

$$\begin{aligned} K_t(h_j) &= 3683.7 + 6637.16e^{-49.3h_j}, \\ K_r(h_j) &= 1942.2 + 3901.8e^{-44.6h_j}, \\ K_a(h_j) &= -214.9 - 3444.8e^{123.1h_j}. \end{aligned} \tag{5}$$

6. CONCLUSION

In summary, solid modeling can provide accurate geometric information of cutting process, but the process involves a lot of Boolean operations. The more complex the solid topology is, the more time and cost it will consume. So much so that it could not be accepted in the actual engineering application. The Z-Map method loses the geometrical accuracy for the discrete expression of cutter and workpiece geometry. Increasing the grids density can improve the accuracy, but reduce the computational efficiency. Analytic modeling methods describe the geometric relationship between cutter and workpiece with formulas in machining process, which has high efficiency and high accuracy.

Cutting force assessment is a crucial research topic because it is very important for the understanding of the machining process, providing many advantages in terms of process optimization. Based on the IMCS and ITCS, a motion model of the ball end mill for the sculptured surface is established. The motion state and the contact relationship between the cutter and workpiece could be described in a quantitative way and it could be a significant material for future papers and experiments.

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Stojanović, J., Pjević, M., Popović, M., Mladenović, G. [2)]

TRENUTNO STANJE U NAUCI U OBLASTI PREDIKCIJA SILE REZANJA KOD GLOGANJA LOPTASTIM GLODALOM

Rezime: *Predikcija sile rezanja predstavlja veoma bitan faktor pri podešavanju parametara procesa obrade i praćenja stanja u kome se mašina nalazi. Kako bi se mogla predvideti sila rezanja kod obrade loptastim glodalom neki od parametara procesa obrade koje je potrebno proučiti predstavljaju geometrija alata, sečiva, kao i kontaktne površime između alata i dela. Kvalitet obrađene površine loptastim glogalom od izuzetnog je značaja iz razloga što ovaj proces definiše funkcionalnu upotrebu dobijenog dela. U ovom radu predstavljemo je trenutno stanje u oblasti isrtažavanja predikicje sila rezanja nastalih usled obrade loptastim glodalom.*

Ključne reči: *Sila rezanja, Glodanje loptastim glodalom, složene površine, CAD/CAM.*