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Determination of cutting forces in ball-end milling with neural networks*

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The paper presents the system for determination of the cutting process on the model of the milling process with neural networks. The system is intended for the determination of cutting forces with given cutting conditions. The basic concept included is the mathematic representation of the relations between tool and workpiece, determined by the function for the chip thickness and the equation for cutting forces. The system is based on the neural networks which predicts the cutting forces. The system can previously show all the important cutting process variables which will later actually appear in the machining process itself.

1. INTRODUCTION

The research in the area of cutting covers a very wide range because, there are many independent influencing factors which appears in the cutting process. Those factors include the cutting parameters (feed rate, cutting speed, cutting width and depth), material properties, properties of the machine-tool-workpiece system, material and tool geometry. In addition to the high number of the influencing factors the problem is complicated by the nonstationary nature of the cutting process.

It is desired to develop the basic procedures for the analysis and determination, which can be applied to a wide area of machining operations. However, that is a very complicated because the developed methods are usable only for very narrow areas. The developed analytical methods are valid only for too limited range of cutting parameters. For practice the most suitable model would be the model which would contain the basic cutting processes by taking the material and the wide spectrum of cutting parameters into account.

The existing knowledge about the cutting forces gives support in planning of the process, in selecting of suitable cutting conditions for reduction of excessive wear, deformation and breakage of the tool.

2. CUTTING FORCES IN BALL-END MILLING

In this chapter, a general model for the determination of cutting forces in ball-end milling operations is presented. The basic concept presented is the mathematical representation of relations between the milling cutter and workpiece, the change of chip thickness and the

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milling cutter rotation angle. [1] The cutting forces are divided into differential cutting forces depending on the number of cutting edges, cutting edge length and milling cutter rotation angle.

2.1. Determination of cutting forces during ball-end milling

The equation for the tangential cutting force, radial cutting force and axial cutting force is:

$$dF_{T,R,A} = K_{T,R,A} \cdot h_b \cdot db = K_{T,R,A} \cdot f_{z_b} \cdot sin\,\mathrm{B} \cdot sin\,\eta \cdot db \quad (1)$$

K_T - tangential coefficient of material
K_R - radial coefficient of material
K_A - axial coefficient of material
db - differential length of cutting edge
h_b - chip thickness
f_{zb} - feeding per tooth
η - angular position in the direction of Z axis from the center of the hemispherical part to the point on the cutting edge
$\mathrm{B}(i,j,k)$ - Angular position of the cutting edge during cutting
dz - differential length of axial differential elements

The generalized equation for the tangential, radial and axial cutting force is:

$$dF_{T,R,A}(i,j,k) = K_{T,R,A} \cdot f_{z_b} \cdot sin[\mathrm{B}(i,j,k)] \cdot dz \quad (2)$$

The forces expressed in the Cartesian coordinate system are obtained if the transformation matrix [T] is inserted [2]:

$$\{dF_{X,Y,Z}\} = [T]\{dF_{R,T,A}\} \quad (3)$$

$$[T](i,j,k) = \begin{bmatrix} -sin\,\eta(i)\,sin\,\mathrm{B}(i,j,k) & -cos\,\mathrm{B}(i,j,k) & -cos\,\eta(i)\,sin\,\mathrm{B}(i,j,k) \\ -sin\,\eta(i)\,cos\,\mathrm{B}(i,j,k) & sin\,\mathrm{B}(i,j,k) & -cos\,\eta(i)\,cos\,\mathrm{B}(i,j,k) \\ cos\,\eta(i) & 0 & -sin\,\eta(i) \end{bmatrix} \quad (4)$$

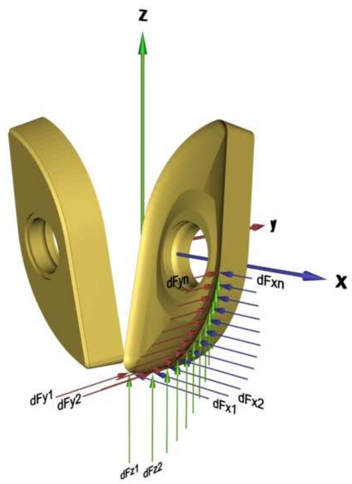

Figure 1. Differential cutting forces

$$\left[dF_{X,Y,Z}(i,j)\right] = \sum_{k=1}^{N_f} [T](i,j,k)\left[K_{R,T,A}\right] \cdot f_{z_b} \cdot \sin[\mathrm{B}(i,j,k)] \cdot dz \quad (5)$$

The total force on the cutting edge in case of j-th position:

$$\left[dF_{X,Y,Z}(j)\right]=\sum_{i=1}^{N_z}\sum_{k=1}^{N_f}[T](i,j,k)\left[K_{R,T,A}\right]\cdot f_{z_b}\cdot sin[\mathrm{B}(i,j,k)]\cdot dz \tag{6}$$

The average cutting force is:

$$\left[\overline{F}_{X,Y,Z}\right]=\left\{\sum_{i=1}^{N_z}\sum_{j=1}^{N_\theta}\sum_{k=1}^{N_f}[T](i,j,k)\left[K_{R,T,A}\right]\cdot f_{z_b}\cdot sin[\mathrm{B}(i,j,k)]\cdot dz\right\}\Big/N_\theta \tag{7}$$

3. ARCHITECTURE OF NEURAL NETWORK AND ITS ADAPTATION TO THE CUTTING FORCES

For the experiment the feed forward and radial basis neural networks were used. The feed forward neural networks give more accurate results, but they require more time for training and testing. The programme containing this network is slow. Therefore the radial basis neural network was chosen for application. Precision of results is worse, but the network is very fast and reliable. Those neural networks require more neurones than the standard feed forward neural networks with the Back Propagation (BPN) Learning Rule, but conceiving of radial basis neural networks lasts only a part of time necessary for training of the feed forward network. The radial basis network is improved with the algorithm that finds the smallest required network which still solves the problem with the given acceptable error.

4. COMPARISON OF THE EXPERIMENTAL MODEL WITH THE EMPIRICAL MODEL

An extensive number of tests were made on the milling machine to confirm the empirical model with different cutting parameters. [3] This chapter presents the results of experiments and the comparison and analysis of results between the experimental and empirical model depending on the cutting parameters. The comparison of values between the assumed cutting forces with the empirical model and the measured cutting forces is presented. The results and/or the values of cutting forces are graphically represented by means of diagrams depending on the angle of rotation of the milling cutter.

By comparing the results obtained by simulation with the results of experiments the following was established: the values from simulation coincide well with the values from experiments and in addition, the process of the change of the cutting force with respect to the angle of rotation of the milling cutter and the amplitude agree well.

Also the comparison of maximum values of the cutting forces from simulation with the experimental values in case of different cutting conditions was made. Further the differences (in %) between the simulation results and the results of experiments for average cutting forces were dealt with. The results mutually differ as follows: from 5-13% for F_X, from 3-6% for F_Y and from 3-8% for F_Z. On the basis of the obtained results the operation of the empirical model of cutting forces can be confirmed by experimental results.

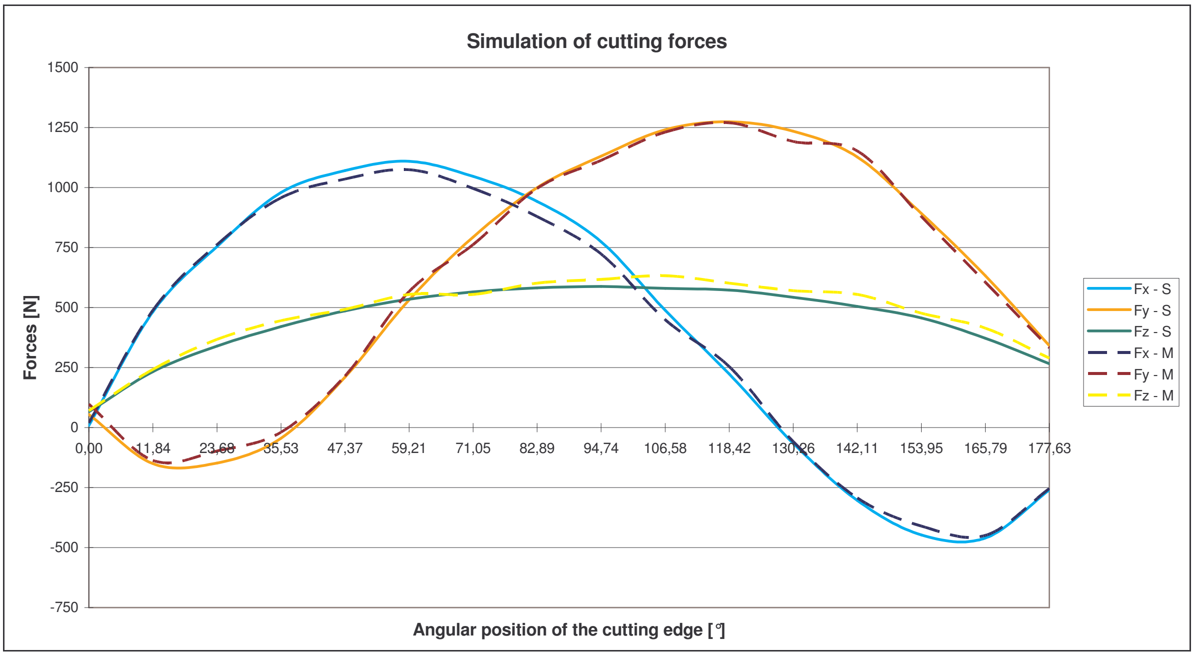

Figure 2. Representation of measured (F_X-M, F_Y-M, F_Z-M) and simulated (F_X-S, F_Y-S, F_Z-S) cutting forces. Ball-end milling cutter R216-16B20-040, cutting insert R216-16 03 M-M GC 4040, material Ck 45, milling width R_D=16 mm, milling depth A_D=8 mm, feeding f_z=0,025 mm/tooth and cutting speed V_c=500 min^{-1}.

5. CONCLUSION

The paper is concerned about the development and use of the system for simulation of the cutting process - cutting forces in ball-end milling. The system was developed by systematic approach and empirical formulation of components of cutting forces for the ball-end milling cutter with neural networks. All influencing factors: tool geometry, workpiece material, and cutting parameters were considered.

It can be claimed that the comparison of the results obtained from the empirical model and of the experimental results confirms the efficiency and accuracy of the system for simulation of the cutting process in predicting the cutting forces. The system for simulation of the cutting process presents an approach to predicting the cutting forces in the milling process and opens new possibilities for optimization of the cutting process, manufacture of new shapes of tools and greater utilization of the machine tools.

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