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Procedia CIRP 31 (2015) 435 – 440

www.elsevier.com/locate/procedia

15th CIRP Conference on Modelling of Machining Operations

Mechanistic model for prediction of cutting forces in turning of non-axisymmetric parts

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Abstract

Most of the existing mechanistic (semiempirical) models for turning are orientated towards continuous cut and are applicable neither to non-axisymmetric parts, nor to the particular case of interrupted turning, so common in real workpieces. Some commercial software packages which simulate machining process by FEM enable to calculate interrupted cut. However, their high computational cost limits the simulations to a very short length of cut, hardly completing one cutting revolution.

By contrast, mechanistic models are not as computationally expensive as FEM ones. Despite their limited accuracy, they give approximate estimations of cutting forces during a whole tool path. Consequently, they are extremely useful to detect critical tool path steps, adapt cutting parameters and avoid machine overload.

This study presents a mechanistic model to predict orthogonal turning forces in 3 directions (*XYZ*), torque and power consumption along the machining path of non-axisymmetric parts. The model communicates with CAM software by automatically transferring information about tool path and geometry from the CAM to the mechanistic model in standard format, contained in CL (Cutter Location) and STL (Stereolithography) files, respectively. Thus, the model is suitable to be integrated into any commercial CAM software. The simplicity of the model, the communication with CAM and an easy-to-use interface aim to spread out the applicability of the model among machining companies. The results of the study are validated by comparing simulations to experimental turning tests.

Peer-review under responsibility of the International Scientific Committee of the “15th Conference on Modelling of Machining Operations

Keywords: Turning; Predictive model; Force; Computer Aided Manufacturing (CAM)

1. Introduction

Modelling of machining efforts is a notorious research field in the metal cutting sector. FEM based and mechanistic models are broadly applied to study cutting forces as well as vibration, tool wear, residual stresses and even metallurgical changes. FEM based models are able to simulate the cutting process for one or two revolutions, predicting any kind of physical phenomena describable by finite elements. Although results show quite accuracy, computational cost is expensive.

Empirically obtained coefficients are the foundation for mechanistic models which, even not so accurately, are able to calculate cutting efforts for a complete tool path. The most common models are the exponential one proposed by Victor-Kienzle [1] and the linear one including ploughing effect proposed by Armarego [2]. In either case, forces are proportional to chip instant area and cutting coefficients. Many improvements have been done to these models, such as Tuysuz et al. [3] who added the effect of more physical phenomena, for example tool indentation. Other authors such as Zatarain et al. [4] have used the same principles to predict chatter instability instead of calculating forces.

The effect of rake angles is usually included within the cutting coefficients by using Altinta’s formulation [5], which can be expressed directly as a function of average shear stress, shear angle, average friction angle and rake angles of the tool. This method is based on macro-mechanics of orthogonal cutting. When the cutting coefficients are found from the slope or trend of the force measurements, the method is called mechanistic modelling.

Furthermore, as it directly influences the simulation speed and memory requirements, the calculation of tool-workpiece

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doi:10.1016/j.procir.2015.03.084

engagements is also object of study [6], [7]. Most authors determine engagement domains by analytic, B-Nurbs, dexel, voxel, and STL triangulation representations.

This kind of models can be applied for most metal cutting processes, for instance, turning, milling, drilling, boring or broaching and even complex ones such as thread milling [8] .

In particular, milling process has been widely addressed and several advances have been conducted in terms of CAM integration, [9], [10] and [11], for instance. Tunc and Budak [12] created a model that uses the information contained in the CL file (Cutter Location file) supplied by the CAD/CAM software and the STL (Stereolithography) of the geometry to analytically calculate the milling conditions. In contrast, there is no cutting forces turning model integrated in CAM turning and multitasking modules. However, in multitasking applications some operations are likely to be applied in previously machined parts, which are not necessarily axysimmetric.

Consequently, the simplicity of the model, the communication with CAM and an easy-to-use interface aim to spread out the applicability of the model among machining companies.

This study presents a mechanistic model to predict orthogonal turning forces in 3 directions (XYZ), torque and power consumption along the machining path of non-axisymmetric parts. To explicitly include the effect of the rake or side angles in the formulation, the model should consider micro-mechanics of metal cutting, which would require a higher level of detail (FEM) and higher computational time, so coefficients are experimentally calibrated. In fact, there are commercial software packages, such as Third Wave AdvantEdge©, which enable to define all these geometric parameters of the tool. Consequently, it is not the issue of this study to cover the same field of the commercial ones, but develop a complementary model providing quick information, although not so accurate, in a short calculation time about the cutting forces in the whole process.

The model communicates with commercial CAM software by automatically transferring information about tool path and geometry from the CAM to the mechanistic model in standard format, contained in CL and STL files, respectively. Thus, although the commercial CAM software used in the current work is the turning module of NX©, the model is suitable to be integrated into any other CAM software.

Together with a simulation, an experimental turning test has been conducted as a validation of the results of the study. Furthermore, a discussion of a practical case has been included about how the cutting forces could be reduced by changing the lead angle (κ_r). It shows the utility of the model for a particular example, related mainly to calculation time. Results have been compared to simulations with the commercial software Third Wave AdvantEdge©.

2. Simulation steps

2.1. Data reading (Pre-processing)

One of the main features of this model is its communication with commercial CAM software, NX©. Most input data needed by the model for the simulation are automatically taken from CAM software and transformed into two main files:

- CL file including tool path, tool geometry and workpiece material.
- STL file containing the initial blank 3D geometry.

CL file

CL files are automatically generated by NX© and include the following information, taken from NX© definition dialogs:

- Tool path: XYZ coordinates, orientation and cutting velocities. See Fig. 1.

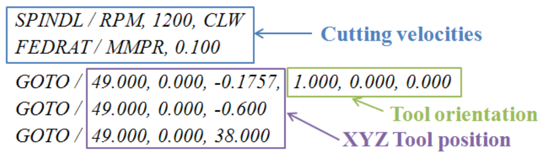

Fig. 1. XYZ coordinates and cutting parameters.

- Tool geometry
  TOOL PATH / ROUGH_TURN_OD, TOOL, OD_80_L
  TLDATA / TURN, LEFT, OUTSIDE, MCSZ, 2.000, 4.000, 5.000, 5.000, 150.000, 290.000
- Workpiece material:
  PART_MATERIAL CARBON STEEL

STL file

Represented by triangular faces, in this file the blank geometry that will be machined is included. Although other standard formats such as IGS, Parasolid or STEP are more accurate, STL format is the most suitable one when representing very complex unparameterized geometries. The blank geometry can be a user's predefined geometry or the result of previous machining steps.

2.2. Mechanistic calculation

This work proposes a model built from the expressions presented by Altintas [13] which uses six empirical specific cutting coefficients: K_{tc}, K_{rc}, K_{ac}, K_{te}, K_{re} and K_{ae}.

The basic equation of the force model includes two actions:

- Given by the K_{ic} coefficients (where i means tangential, radial or axial), the force component associated to the material shearing action, proportional to undeformed chip cross-sectional area: dA_c.
- Given by the K_{ie} coefficients, the component associated to the friction, rubbing and ploughing actions, proportional to elementary length of the cutting edge: dS.

$$dF_t=K_{te}dS+K_{tc}dA_c \quad (1)$$
$$dF_r=K_{re}dS+K_{rc}dA_c \quad (2)$$
$$dF_a=K_{ae}dS+K_{ac}dA_c \quad (3)$$