COMPUTATIONAL MECHANICS 2018
34th conference with international participation
Srní
October 31 - November 2, 2018

Coordinate-free formulation of the cutting process

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Machining processes are invaluable in many industrial branches. Calculation of the cutting forces is important for quality prediction of the machined surface. The cutting forces are usually expressed and manipulated in a certain coordinate system. So long the geometry of the cutting process is simple, the approach works well, however dynamics of more general operations like 5-axis milling are often difficult to describe without some additional simplifications.

The total cutting force is a result of the pressure/friction fields acting on the tool-workpiece contact. For practical purposes, empirical expressions for the specific cutting force acting on an 1-D element of cutting edge are used—specific force $\mathbf{f}$ per unit chip width is introduced. It depends on local cutting process parameters like for instance the undeformed chip width h, the inclination angle λ or the rake angle α. The basis for the specific force is bound to the cutting edge geometry and its motion - tangential direction given by the cutting velocity $\boldsymbol{t}$, the normal direction by a normal $\boldsymbol{n}$ to the surface created by the cutting edge in space. The third basis vector $\boldsymbol{b}$ is perpendicular to both $\boldsymbol{t}$ and $\boldsymbol{n}$, see Fig. 1a.

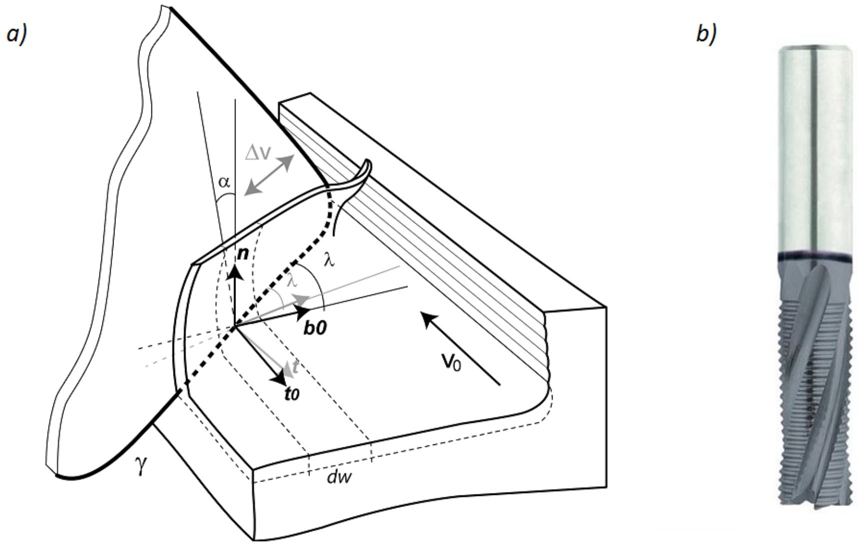

Fig. 1. a) Local force basis on the cutting edge element, b) serrated milling tool

The total cutting force is calculated as an integral over the cutting edges in contact with the workpiece

$$\boldsymbol{F} = \int_{\gamma} \mathbf{1}_S \, [\boldsymbol{t}\,\boldsymbol{n}\,\boldsymbol{b}] \, \mathbf{f}(h, \lambda, \alpha) dw \,,$$

where $\mathbf{1}_S$ is a characteristic function which is 1 if the element is in the engagement area S and 0 otherwise.

Probably the most important property of the tool-workpiece dynamic is its stability. Its calculation requires knowledge of the systems reaction to a small variation of the system's kinematics due to small vibrations. The first step of the coordinate free approach are definitions of all necessary cutting process parameters and basis vectors with respect to a chosen set of vector functions describing the unperturbed kinematics of the system and the geometry of the tool, e.g. axis of spindle rotation, feed direction, curves describing cutting edges. The characteristic function needs to be defined through coordinate free scalar constraints, e.g. non-negative chip thickness. In the second step variation of the total force with respect to a small perturbation of the kinematics is calculated. Virtually all the functions in the integrand may be affected by the perturbation.

The contribution of the characteristic function $\mathbf{1}_S$ to the cutting force differential requires application of Leibniz integral rule and implicit function theorem. A special case of this effect was studied by Eynian as an influence of tool tip radius on stability [3].

The transformation matrix $[\boldsymbol{t}\ \boldsymbol{n}\ \boldsymbol{b}]$ and the technological angles are affected by perturbation of tool/workpiece relative velocity direction. These effects were studied on 2-D tool geometries by Das and Tobias in 1967 [1]. They are rarely taken into account in the models of machining dynamics (recent exception being Molnar's article about process damping [4]).

The specific force is affected by the perturbation via the technological angles and the undeformed chip thickness h, which depends not only on perturbation of the actual position but on a past perturbation that deformed the new surface in the previous cut. This so called regenerative effect was discovered by Tlustý and Poláček in the early 1950s [5].

The resulting formula for the perturbed cutting force is too long to be presented here. The advantage of the coordinate free approach is that it allows formulation of the machining stability generally without limitation on the type of the cutting process or direction of the perturbation.

Another application of the coordinate free approach is calculation of more general undeformed chip thickness formula. It can be shown that the commonly used formula based on tool envelope normal and tool-workpiece displacement does not hold for serrated milling tools, see Fig. 1b. It means that the current analyses of machining stability for various serration are based on an incorrect model, e.g., Dombovari [2].

Acknowledgement

This work was supported by the Grant Agency of the Czech Technical University in Prague, grant No. SGS16/220/OHK2/3T/12.

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