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Generalized mechanics and dynamics of metal cutting operations for unified simulations

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ABSTRACT

This paper presents the unified modeling of mechanics and dynamics of metal cutting operations such as turning, boring, drilling and milling. The distribution of chip thickness along the cutting edges of tools are evaluated using the generalized geometric and kinematic model of the operations [1]. The effect of relative vibrations between the cutting edge and workpiece segments are considered. The force contributed by each oblique cutting edge segment is evaluated from shear stress, shear angle and friction coefficient defined in orthogonal cutting data base. The tool cutting loads are evaluated by summing the differential cutting forces along all engaged cutting edges using the generalized geometric transformations presented in [1]. The chatter stability is solved in modal coordinate system, and the forced vibration marks left on the finish surface are predicted in discrete time domain. The process damping, multiple-regenerative phase delays which depend on the tool geometry and operations are considered. The application of the proposed unified mechanics and dynamics model is demonstrated experimentally in drilling, milling with indexable cutters and various end mills, and in opening large holes with multi-functional drilling/boring heads.

1. Introduction

The aim of metal cutting mechanics and dynamics is to predict torque, power, force, dimensional surface errors, vibrations, and chatter free conditions for all cutting operations. There has been significant amount of research reported in the literature for classicial machining operations with tools having standard geometries. Whenever the tool geometry becomes specific for an application, such as form cutters, multi-functional or serrated tools, it has been customary to develop a dedicated mathematical model for each case. Since the physics of mechanics and dynamics are the same, the authors proposed a unified mathematical model for all metal cutting operations. The geometry of tools and kinematics of standard cutting operations are unified in one mathematical model as a first step, and presented in [1]. This paper uses the unified geometric model of the tools in developing a common mechanics and dynamics model for a variety of metal cutting operations such as turning, drilling, boring and milling.

The mechanics of a basic oblique cutting process which is common to all operations with geometrically defined edges is shown in Fig. 1 [2]. The friction and normal forces at the chip-rake face contact zone are predicted as:

$$F_u = K_{uc}A_c; \quad F_v = K_{vc}A_c, \tag{1}$$

where A_c is the uncut chip area and K_{uc}, K_{vc} are cutting force coefficients which are dependent on the cutting edge geometry and work-material properties. The cutting force coefficients can be either calibrated mechanistically from cutting tests directly for each tool and operation [2–4] or through orthogonal [5] to oblique cutting transformation by using shear stress, shear angle and friction coefficients of materials [6]. Static edge ploughing [7], indentation of the edge into metal with zero velocity [8,9], and process damping [10,11] forces need to be considered depending on the tool geometry, speed and feed direction. Engin et al. [12] presented a generalized, parametric model of solid and indexable milling tools to predict the cutting forces. Kaymakci et. al. presented a unified geometric model of milling, turning, drilling and boring tools with inserts having flat rake face and standard cutting edge geometry [13]. Altintas and Kilic extended the model to include chip regeneration in dynamic cutting [14].

The dynamics of metal cutting operations have also been extensively studied to predict forced vibrations and chatter stability

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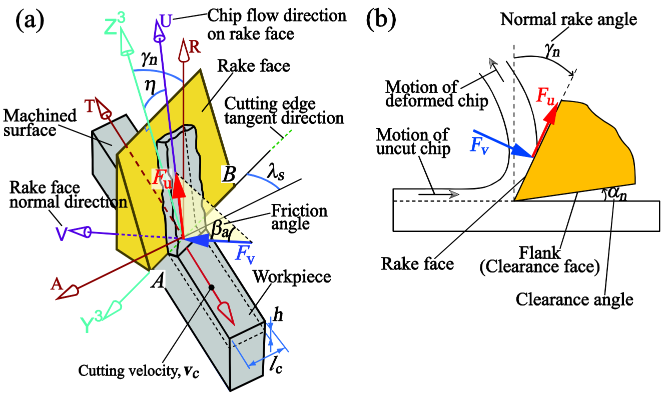

Fig. 1. Schematics of chip removal at differential cutting edge element. (a) Oblique cutting with rake face forces shown. (b) Orthogonal cutting in cutting edge normal plane view

both in frequency and discrete time domains. Pioneering theories of Tlusty [15] and Tobias [16] predicted the chatter stability of one dimensional machining systems in frequency domain, i.e. lumped dynamics at the turning tool. The stability of multi-dimensional machining systems, where the dynamics may be different and coupled in three translational and torsional directions with periodic coefficients, have also been solved both in frequency [17,18] and discrete time domains [19]. The cutting forces and surface location errors for helical end mills have also been studied [19,20]. However, there has not been any research which unifies the geometry, mechanics and dynamics of all metal cutting operations in one, generalized mathematical model. The generalized, parametric geometric model of the cutting tools are defined while considering the kinematic configuration of the operation (i.e. turning, milling, drilling, boring) in the first part of the research [1].

This paper presents the unified modeling of all metal cutting operations to predict force, torque, power, vibrations, surface location errors and chatter stability by using the generalized geometric model. The cutting edges are represented by an assembly of discrete elements, and the cutting force distribution at each discrete edge is predicted using orthogonal to oblique cutting transformation. The metal cutting process forces at the cutting edge are transformed to tool body and process coordinate systems by considering the kinematics of each operation type (i.e., turning, boring, drilling and milling) and tool geometry. The equation of motion for the generalized system is constructed either at one point if the tool–workpiece dynamics is lumped, or distributed at the tool–part contact area if the dynamics are distributed. The application of the general model is demonstrated in turning, milling, drilling, boring with standard and varying configurations.

2. Generalized modelling of metal cutting mechanics

The metal chip is plastically sheared from the workpiece material in shear zone, and the deformed chip slides on the rake face of the tool experiencing both sticking and sliding friction as shown in Fig. 1 [2]. The shear angle, average shear stress and average friction between the moving chip and stationary tool surface are used to predict the cutting forces, torque and power in orthogonal cutting where the cutting edge is perpendicular to the cutting velocity, (i.e., zero inclination angle, $\lambda_s = 0$ in Fig. 1). When the cutting edge is inclined relative to the cutting velocity, the process becomes oblique with cutting forces in radial, tangential and axial (RTA) directions ($\lambda_s \neq 0$). While orthogonal cutting process is used to identify the fundamental process parameters such as shear stress, shear angle and friction angle (β_a), most cutting tools used in practice have oblique tool geometry.

The tool geometry is generalized by using the position vector, tangent vector and rake face orientation at each point along the entire cutting edge in the geometric modeling paper [1], which is used to model the chip geometry and cutting process mechanics. The kinematics of turning, boring, drilling and milling operations are developed to transform the process forces and vibrations at the desired tool and part locations. This section presents the modeling of chip thickness and cutting forces at the tool-part contact zones.

2.1. Review of generalized tool geometry

Generalized modeling of tool geometries is given in [1,21], and briefly recapitulated here. Cutting tool is segmented into small discrete elements along the cutting edge. Position of each discrete element, and the vectors that are tangent to the cutting edge and rake surface are defined in Frame 0 as:

$$\mathbf{T}_{\mathrm{I}}^{0} = \begin{bmatrix} \mathbf{R}_{\mathrm{I}\,(3\mathrm{x}3)}^{0} & {}^{0}\mathbf{r}_{(3\mathrm{x}1)}^{\mathrm{I}} \\ \mathbf{0}_{(1\mathrm{x}3)} & 1 \end{bmatrix}_{(4\mathrm{x}4)} \rightarrow \mathbf{p}_{(4\times4)}^{0} = \mathbf{T}_{\mathrm{I}}^{0}\mathbf{p}_{(4\times4)}^{\mathrm{I}} \qquad (2)$$

where origin of Frame I is located on insert for indexable cutters, on the edge element for solid tools. Z^0 axis of Frame 0 corresponds to tool axis direction for milling, tool axis and assumed feed directions for drilling and boring, workpiece axis and assumed feed directions for turning operations. X^0 axis of Frame 0 is the assumed feed direction for milling.

The information stored in Eq. (2) leads to the prediction of local rake and inclination angles which are needed in cutting mechanics. The transformation is continued until mapping all C number of discrete elements to form the complete cutting edge on the tool body. The entire cutting edge with possible geometric variations along the tool axis is completely defined as a whole body by an array of points $\mathbf{P}^0(\mathbf{p}_1^0, \mathbf{p}_2^0, .., \mathbf{p}_C^0)_{(4\times(4C))}$ with their coordinates and orientation vectors in Frame 0. Once the tool is constructed geometrically, it is re-segmented into small discrete oblique cutting disk elements in axial (i.e., cylindrical milling tools) and/or radial (i.e., turning, boring, drilling) directions. An arbitrary tool geometry for any cutting operation is defined by 15 parameters, for each cutting edge element S_{jk}, as follows:

- Location in Cartesian coordinates (x^0, y^0 and z^0)
- Whether the edge element is engaged with the work material (g_1)
- Axial depth and axial runout,
- Radius, R, radial depth and radial runout,
- Angular location, $\psi(j,k)$ / $\psi^{\mathrm{rel}}(j,k)$, and pitch angle, $\phi_{\mathrm{p}}(j,k)$,
- Angular orientation of the rake face (normal rake angle, γ_{n} inclination angle, λ_{s} and cutting edge angle, κ_{r}).

The implementation of each parameter in turning, boring, drilling and milling tool geometries is explained in the first part of the article [1]. The definition of tool geometry leads to the derivation of chip geometry, related forces and transformations for metal cutting operation as follows.

2.2. Distribution of chip geometry along the cutting edge

Chip thickness, $h(j,k,i)$ is defined in the radial (R) direction of the cutting edge element S_{jk} with static, $h_{\mathrm{st}}(j,k,i)$ and dynamic, $h_{\mathrm{d}}(j,k,i)$ components:

$$h(j,k,i) = h_{\mathrm{st}}(j,k,i) + h_{\mathrm{d}}(j,k,i). \qquad (3)$$