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A generalised geometrical model of turning operations for cutting force modelling using edge discretisation

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ABSTRACT

The knowledge of cutting forces is of prime importance to ensure the success of cutting operations, the desired properties of the machined parts and therefore the functionality of the workpieces. Edge discretisation is one way to model cutting forces. Traditionally used in milling, this methodology enables local changes in uncut chip thickness or cutting geometry to be taken into account and then gives suitable results in the three directions. A key point of this method is the geometrical transformation that enables the description of various tool geometries. This study proposes a geometrical model based on homogeneous matrices, whose main interest is to decompose the transformations step-by-step. The method, generalisable to all machining operations, is detailed for turning operations. Inserted cutters are modelled considering both the positioning of the insert and the local geometry of the insert. The cutting geometry and the edge are described using the same model in the machine coordinates system, allowing forces and moments to be calculated easily.

1. Introduction

The modelling of cutting forces is essential to predict the progress of machining operations as well as the final properties of workpieces. At a large scale, the cutting forces can be used to size the clamping system [4] or to predict the deflections [5] or the vibrations [6–11] of the tool, the part or the structure, in order to ensure the geometry and the roughness characteristics of the machined surface. When focusing on the tool-part interface, numerous studies have tried to link cutting forces to residual stresses [12] or surface integrity, and then predict fatigue life or corrosion resistance [13].

More and more manufacturers wish to adapt the cutting parameters in order to obtain the expected properties of the workpiece. For example, the feed can be modified along the tool path in order to limit the cutting forces, while minimising the cycle time [14,15]; the machining allowance may also be variable. The feed can be adapted in real-time by measuring the forces and modifying the numerical command (NC) instructions [16]. Nevertheless, predictive methods should be preferred because of the cost of the monitoring equipment and the difficulties in modifying the NC command data or the set-point value in the speed control loop. Moreover, simply respecting a maximum force does not ensure the smooth progress of the cutting process. As a consequence, there is a need for cutting force models which can be used for complex and various cutting operations.

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Nomenclature

α_{ne}	working normal clearance angle; defined in P_n [1]
α_n^P	normal clearance angle given by the local preparation (P) of the insert; defined in P_n
α_{oe}	working orthogonal clearance angle; defined in P_{oe} [1]
γ_{ne}	working normal rake angle; defined in P_n [1]
γ_n^P	normal rake angle given by the local preparation (P) of the insert; defined in P_n
ε^E	tool included angle of the cutting edge (E); also denoted ε_r if the cutting edge is included in P_r [1]
η	chip flow angle
θ	polar angle defined in a coordinate system linked to the insert (parameterisation of the cutting edge)
Θ	polar angle defined in a coordinate system linked to the machine ($\Theta = \theta + \kappa_r + \varepsilon_r/2 - \pi/2$)
κ_r'	tool minor cutting edge angle; defined in P_r [1]
κ_r^B	tool cutting edge angle of the major cutting edge during cylindrical turning (or κ_r [1])
κ_{re}	working cutting edge angle; defined in P_{re} [1]
λ_{se}	working cutting edge inclination angle; defined in P_{se} [1]
λ^E	inclination angle given by the local curvature of the cutting edge (E)
ψ_f^B	tilting angle defining the positioning of the insert on the tool body (B); defined in P_f
ψ_p^B	tilting angle defining the positioning of the insert on the tool body (B); defined in P_p
A_D	nominal cross-sectional area of the cut [2]
a_p	depth of cut (back engagement of the cutting edge [2])
f	feed [2]
$\overrightarrow{f}$	local linear forces
$\overrightarrow{F}_x$	global force applied to the tool in the machine X axis direction (idem for F_y and F_z)
h	local thickness of cut [2]
h_{max}	maximum uncut chip thickness on the active cutting edge
K_c	specific cutting force
L_S	length of the considered segment
M	current point on the cutting edge
$\mathcal{M}_{x,C}$	moment around $\overrightarrow{X}_M$ at point C
N_{Seg}	number of segments used in the discretisation
P_f	assumed working plane [1]
P_n	cutting edge normal plane [1]
P_{oe}	working orthogonal plane [1]
P_p	tool back plane [1]
P_r	tool reference plane [1]
P_{re}	working reference plane [1]
P_{se}	working cutting edge plane [1]
r_β	rounded cutting edge radius (standardised notation: r_n [1])
r_ε^E	corner/nose radius; also denoted r_ε if the cutting edge is included in P_r [1]
R^E	polar radius (parameterisation of the cutting edge)
R_o^W	radius of the workpiece (W) in the plane P_o
$\overrightarrow{v}_c$	local cutting speed [1]
$\overrightarrow{v}_e$	local resultant cutting speed [1]
$\overrightarrow{V}_f$	feed speed [1]
x^M	machine axis translation in the X direction (defined by [3])
z^M	machine axis translation in the Z direction (defined by [3])

In a literature review conducted in 1998 [17], the authors noted that cutting force models are too rarely used in industry, because they are not well formalised and the validity domain is not clearly specified.

The aim of the present study is to propose a methodology which enables the description of cutting operations when turning with inserted tools.

A brief review of cutting force modelling by mechanistic approaches is first proposed. Then a geometrical model using homogeneous matrix transformations is presented. Next, the cutting geometry is described and the main factors affecting the forces are calculated in order to be used as inputs for the cutting force models. Finally, the forces and moments applied to the tool can be calculated.

In this article, most notations used are consistent with ISO standards [1–3]. The notations $\overrightarrow{F}_x$, $\overrightarrow{F}_y$ and $\overrightarrow{F}_z$ correspond respectively to the radial, tangential and axial components of the global forces (in Newtons). The local forces (in N/mm) are denoted with a lowercase $\overrightarrow{f}$.