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Plunge milling time optimization *via* mixed-integer nonlinear programming ☆

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ABSTRACT

Plunge milling is a recent and efficient production mean for machining deep workpieces, notably in aeronautics. This paper focuses on the minimization of the machining time by optimizing the values of the cutting parameters. Currently, neither Computer-Aided Manufacturing (CAM) software nor standard approaches take into account the tool path geometry and the control laws driving the tool displacements to propose optimal cutting parameter values, despite their significant impact. This paper contributes to plunge milling optimization through a Mixed-Integer NonLinear Programming (MINLP) approach, which enables us to determine optimal cutting parameter values that evolve along the tool path. It involves both continuous (cutting speed, feed per tooth) and, in contrast with standard approaches, integer (number of plunges) optimization variables, as well as nonlinear constraints. These constraints are related to the Computer Numerical Control (CNC) machine tool and to the cutting tool, taking into account the control laws. Computational results, validated on CNC machines and on representative test cases of engine housing, show that our methodology outperforms standard industrial engineering know-how approaches by up to 55% in terms of machining time.

1. Introduction

Several industrial processes, arising for instance in the aeronautical industry, are based on material removing (milling) that can be performed by several techniques. For aeronautical workpieces, the quantity of material to be removed often represents a very large proportion of the stock material. The most efficient milling processes include: high-speed machining (Finzer, 1999; Schulz, 2003), inclined milling with balancing of the transverse cutting forces (Gilles, Monies, & Rubio, 2007; Moussaoui, Monies, Mousseigne, Gilles, & Rubio, 2016), and plunge millling (Danis, Wojtowicz, Monies, & Lagarrigue, 2014; Danis, Monies, Lagarrigue, & Wojtowicz, 2016; Rauch & Hascoet, 2012). Among them, plunge milling is a recognized highly-efficient process thanks to its high removal rate due to its distribution of cutting forces on the tool. More precisely, the radial force that causes chatter is reduced and the axial cutting force generally compresses the tool on the spindle and then increases its stiffness. This strategy is less subject to vibration than the other above-mentioned milling techniques. This is especially crucial for deep milled workpieces. Plunge milling is essentially used for making vertical walls (*lateral plunge milling*), enlarging holes, or slotting (Zhuang, Zhang, Zhang, & Ding, 2012). In the case of lateral plunge milling, the tool moves parallel to the wall to be produced (Zhuang, Zhang, Zhang, & Ding, 2013). The thickness of the wall to be milled determines the radial depth of cut. When plunge milling is used to enlarge holes, all the teeth of the tool cut simultaneously, and the radial depth of cut corresponds to the difference between the radius of the pre-existing hole and that of the tool. In the case of slotting (also referred to as *full-slot plunge milling*), the tool is fully engaged into the material to be milled (see Fig. 1), the cutting width being equal to the tool diameter (Danis et al., 2016). Plunge milling is also called *z-axis milling*, in three-axis machining. It is composed of a sequence of cycles which are repeated along a guide curve provided by a Computer-Aided Manufacturing (CAM) software. Each cycle includes three phases: plunging, rising, and offset (Rauch & Hascoet, 2012). The tool removes material during the plunging phase in the z-axis. Then, it retracts during the rising phase. Finally, it steps over in the x- and/or y-axis during the offset phase so as to make an overlapping vertical cut at the next cycle (Fig. 1).

Recent research on plunge milling optimization focuses on geometry tool selection, tool path generation, cutting parameters,

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Nomenclature

Decision variables

V_c	cutting speed (m/min)
f_z	feed per tooth (mm/rev/tooth)
a_e	radial offset (mm)
N_p	number of plunges

Input parameters

L	elementary trajectory length (mm)
L_p	plunging length (mm)
L_r	rising length (mm)
L_o	offset length (mm)
T	machining time (s)
t_p	plunging time (s)
t_r	rising time (s)
t_o	offset time (s)
i	label of an axis ($i \in \{x, y, z\}$)
V_f	programmed feedrate (m/min)
$A(t)$	acceleration vector at time t (m s^{-2})
A^{max}	maximum absolute value of $A(t)$ (m s^{-2})
$V_s(t)$	speed vector at time t (m/min) for the Soft control law
$V_b(t)$	speed vector at time t (m/min) for the Brisk control law
V_s^{max}	maximum value of $V_s(t)$ (m/min)
V_b^{max}	maximum value of $V_b(t)$ (m/min)
Z	number of teeth
D	tool diameter (mm)
P^{max}	maximum machining power (kW)
F_t^{max}	maximum tangential cutting force (N)
F_r^{max}	maximum radial cutting force (N)
F_a^{max}	maximum axial cutting force (N)

Lower and upper bounds

P^M	maximum machining power upper bound (kW)
F_t^M	maximum tangential cutting force upper bound (N)
F_r^M	maximum radial cutting force upper bound (N)
F_a^M	maximum axial cutting force upper bound (N)
V_f^M	maximum axis speed reachable (m/min)
V_R^M	maximum rapid speed (m/min)
A^M	maximum axis acceleration reachable (m.s^{-2})
J^M	maximum axis jerk (m s^{-3})
a_e^m, a_e^M f_z^m, f_z^M V_c^m, V_c^M	lower and upper bounds on the decision variables

and kinematic capabilities of the machine tools. According to the type of operation (example: roughing pockets, roughing turbine blades, etc.), the tool path can be optimized. For example, Ren, Yao, Zhang, Xue, and Liang (2009) and Sun, Wang, and Huang (2015) study plunge milling tool-path generation. The former optimize the machining time, while the latter concentrate on improving the cutting efficiency and increasing the life time. More recently, Han, Zhang, Luo, and Wu (2014) propose a method for optimizing both the plunge tool selection and the tool path generation in the case of rough machining of free-form surface impellers. Remark that in the context of *pocket milling*, (Banerjee, Feng, & Bordatchev, 2012) also optimizes both the tool-path generation and the machine-tool speed (*feed*) under cutting-force constraints.

Studies that rely on the cutting parameter optimization to improve the plunge milling efficiency are relatively rare. These parameters determine the cutting forces, the power consumption of the spindle, the stability in machining, and the metal removal rate. Zhuang et al. (2013) propose an optimization of some cutting parameters in the case of lateral plunge milling. They consider constraints on cutting forces, cutting parameters, and stability criteria and use the frequency domain method defined in (Ko & Altintas, 2007). Their objective is to maximize the metal removal rate by optimizing the radial depth of cut, the radial offset and the cutting speed. However, in their study, the feed per tooth is not optimized, its value being kept fixed during the optimization process. Furthermore, this optimization is performed by a simple heuristic approach, yielding sub-optimal solutions.

Important factors in machining time include the kinematic capabilities (jerk, acceleration, and maximum speed) of the Computer Numerical Control (CNC) machine tool and the associated control laws. Rauch and Hascoet present in (Rauch & Hascoet, 2012) the impact of these factors, and also an analysis of the performances of plunge milling as a function of both the machine-tool kinematics capabilities and of one specific control law. Despite the relevance of these factors in machining performances, none of the above approaches optimizes simultaneously all the major cutting parameters under kinematic constraints. Moreover, to the

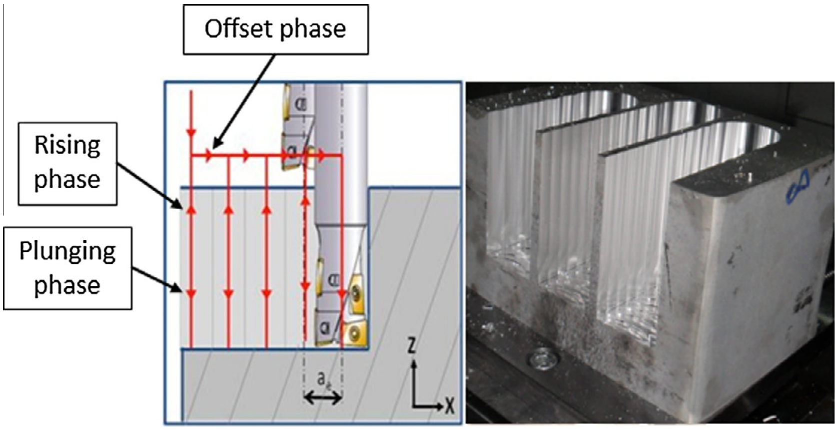

Fig. 1. Plunge milling.