Expert Systems with Applications 40 (2013) 2312–2322

Contents lists available at SciVerse ScienceDirect

Expert Systems with Applications

journal homepage: www.elsevier.com/locate/eswa

Model-based expert system to automatically adapt milling forces in Pareto optimal multi-objective working points

Luis Rubio [a,*], Manuel De la Sen [b], Andrew P. Longstaff [a], Simon Fletcher [a]

[a] Centre for Precision Technologies, University of Huddersfield, Queensgate, Huddersfield, West Yorkshire, HD1 3DH, United Kingdom
[b] Institute of Research and Development of Processes, University of the Basque Country, Barrio Sarriena s/n, 48940 Leioa, Bizkaia, Spain

A R T I C L E I N F O

Keywords:
Milling processes
Expert system
Optimisation
Manufacturing automation
Adaptive forces control

A B S T R A C T

The objective of this paper is to present an open and modular expert rule-based system in order to automatically select cutting parameters in milling operations. The knowledge base of the system presents considerations of stability, machine drives efficiency and restrictions while adaptively controlling milling forces in suitable working points. Moreover, a novel classical cost function has been conceived and constructed to Pareto-optimise cutting parameters subjected to multi-objective purposes, namely: tool-life, surface roughness, material remove rate and stability rate parameter. Different Pareto optimal front solutions can be obtained modulating the weighting factors of the cost function. Additional rules have been added in order to manually and/or automatically modulate this cost function. Furthermore, a database which relates weighting factors, cutting conditions and cost function variables is produced for learning purposes. Chatter detection and suppression system automatically feedback to the system to take into account non-modelled disturbances. Finally, since the knowledge of the system is basically obtained from mathematical models, the possibility of combining experience and knowledge from expert engineers and operators is included. In this way, best practice from mathematical modelling and expert engineers and operators is joined in one system obtaining a full, automated system combining the best of each world.

As a result, the expert rule-based system selects Pareto optimal cutting conditions for a broad range of milling processes, sorting out automatically different problems such as chatter vibrations, incorporating model reference adaptive control (MRAC) of forces. This procedure is intuitive, being executed in the same way as a human expert would do and it provides the possibility to interact with expert engineers and operators in order to take into account their experience and knowledge. Finally, the expert system is designed in modular form allowing incorporating new functionalities in rule based forms to them or just adding new modules to improve the performance of the milling system.

1. Introduction

Despite various attempts at optimization, the selection of cutting parameters for CNC milling operations is still largely driven by machine operators on the shop-floor. They use their experience and/or handbooks in order to program adequate cutting parameters (Balakrishana & DeVries, 1982; Liang, Hecker, & Landers, 2004). Normally, those parameters are selected in an intuitive way and/or using machining handbooks leading to programming cutting parameters under safety upper limits in order to prevent vibrations and process malfunctions. In this sense, automation techniques are being introduced in manufacturing environments to computerize and achieve more accurate solutions due to increase competitive markets. As a first solution adaptive controllers substituted fixed gain controllers in order to behave better under sensible changes in the depth of cut (Koren, 1989). One step ahead is the adaptive optimization of the cutting parameters using intelligent techniques. Those techniques present multi-function optimization through, for example, neural networks, genetic algorithms and other bio-inspired techniques (Avellan, Romeros, Siller, Estrud, & Vila, 2008; Cus & Balic, 2003; Surech et al., in press; Wong & Hamouda 2003b; Zuperl & Cus 2003; Zuperl, Cus, & Milfelner 2005). Nevertheless, those methodologies provide intrinsic mathematical non-linear functions, which learn in hidden "black boxes" from a series of examples, given useful solutions but reducing the transparency of the interfaces.

Furthermore, expert systems have also been developed to cope with this problem. In manufacturing processes, expert systems propose two steps. First, a knowledge base about the system is addressed, and then, some pseudo-heuristic rules are used, extracted from knowledge or experience in order to infer a solution, often using Fuzzy Logic (FL) or reasoning. Some versatile approaches in the literature are, for example; Wong and Hamouda (2003a),

* Corresponding author. Tel.: +44 (0) 1484471805.
E-mail address: L.R.Rodriguez@hud.ac.uk (L. Rubio).

0957-4174 © 2012 Elsevier Ltd. Open access under CC BY license.
http://dx.doi.org/10.1016/j.eswa.2012.10.034

where an online knowledge based fuzzy expert system for machinability data selection using Fuzzy Logic as reasoning mechanism in capturing the knowledge of machining operators is developed. Also in Vidal, Alberti, Ciurana, and Casadesús (2005) computer aided process planning is used for choosing the manufacturing route in metal removal processes and their cutting parameters. On the other hand, Zhang and Lu (1992) discussed an expert system for economic evaluation of machining planning operation through integration of the manufacturing and management systems, trying to plan technical issues tied to the economical ones such as amortization of the machine, taking into account labour, materials and working capacity. In Morgan, Cheng, Altintas, and Ridgway (2007), the milling system is fully diagnosed using FL, providing sources of machining problems and corrective actions. Finally, in Iqbal, He, Li, and Dar (2007), tool life is enhanced and work-piece surface finish improved using experimental data and if-then rules through analysis of variance techniques and numeric optimization. Moreover, some theoretical and experimental work has been carried out in order to get optimal machining parameters subject to dimensional precision and surface quality, tool life expectancy and production times (Chien & Chou, 2001; Vivanco, Luis, Costa, & Ortiz 2004 and references therein); in different machining processes and using different materials.

The term expert system was originally used to denote systems using a significant amount of expert information about a particular domain in order to solve problems within that domain. Due to the important role of knowledge in such systems; they have also been called knowledge-based systems. However, since the terminology has been applied to so many diverse systems, it has essentially evolved into two different uses of the term. First, the term is often used to describe any system constructed with special kinds of "expert-systems" programming languages and tools, including production systems, rule-based systems, frame-based systems, "blackboard" architectures, and programming languages such as LISP or Prolog. Nevertheless, another important feature is that, since expert systems are usually non-deterministic, a large number of modules may be candidates for activation at any given moment. Thus, a criterion is needed to determine how to select which of the applicable modules must be executed next, and what to do after selection. This second type is the more appropriate job of an expert system in the sense that it is a system that "reasons" about the problem in much the same way as humans do.

Despite the fashion of using bio-inspired optimization methods, this work proposes classical optimization methods which allow assembling self-learning and self-adaptive algorithms in a modular way to search for different Pareto optimal solutions. For this purpose, it is used the calculus of optimal working points associated with methods to calculate the stability of the dealt system. Then, the proposed expert rule-based system deals with stability issues and more in-depth analysis can be added. Furthermore, this paper makes an attempt to manage the milling system through reasoning of the possible states in spite of using blackboard architectures.

In this paper, the milling system is described from the point of view of an expert system, but not in the traditional sense where knowledge is extracted from expert engineers' and/or operators' experience. Instead, the dynamic behaviour of the system obtained from theoretical models is used to develop the expert system. Those models of the cutting process consist of the relative compliance between the tool and the work-piece, given by the modal parameters of the used tool. The advantage of this methodology is that the use of mathematical models gives universal solutions in contrast to linguistic solutions which give particular solutions. Moreover, the proposed expert system can be supplemented by semantic-based solutions added in parallel to the modelled expert system, giving the potential to act with the best qualities of each. While this dual method is attractive, care has to be taken of the increase in complexity and cost to develop models of the system and parameterize their constants. This is mitigated in the case of milling since it is a well-known study in literature (Balanchandran, 2001; Budak & Altintas, 1998) and it is possible to take advantage of this extensive literature.

The paper is scheduled as follows. A brief introduction of the dynamic delay differential equation which governs milling systems is initially given. The transfer function which relates forces and programmed feed rates is then explained. This is followed by the development of seven modules which are composed by rules. The first module gives advice about robustness of the system and allowable input cutting parameters; the second one introduces model reference adaptive control of milling forces; the third covers constraints of the spindle and feed drives capabilities; the fourth suggest initial cutting parameters; the fifth model is composed of a novel cost function which measures the performance of the system giving Pareto optimal cutting parameters depending on the milling process to carry out and, the possibility to program different cutting parameters corresponding to different Pareto optimal fronts automatically through the modification of the weighting factors of the cost function; module 6 gives automatic feedback to the system due to non-modelled facts; finally module 7 provides the possibility to interact with expert engineers or operators to input to the system their experience and knowledge. Results clarify the developed work and conclusions and discussion will end the paper.

2. System description

Milling processes are well characterized as mechanical systems which are particularly sensibility to acquiring vibrations. In this section, the milling process is modelled as a second order differential equation, which is excited by forces whose inherent terms excite the modal parameters of the system. This fact results in the conversion of resultant energy into vibrations of the system. Those vibrations are generated under certain cutting conditions depending on the process being carried out, clamping of the workpiece, tool and workpiece materials, etc. (Budak and Altintas,1998; Landers & Ulsoy, 1993).

In this frame of mind, the standard milling system responds to a second order differential equation excited by the cutting forces, $F(t)$ (Budak and Altintas,1998; Landers & Ulsoy, 1993),

$$M \cdot \ddot{r}(t) + B \cdot \dot{r}(t) + C \cdot r(t) = F(t) \tag{1}$$

where $r(t) = \{x(t), y(t)\}^T$ are the relative displacements between the tool and the workpiece in the X–Y plane, $F(t) = \{F_x(t), F_y(t)\}^T$, and M, B and C are the modal mass, damping and stiffness matrices, all of them represented in two dimensions. The milling cutting force is represented by a tangential force proportional with the instantaneous chip thickness, and a radial force which is expressed in terms of the tangential force (Balanchandran, 2001; Budak & Altintas, 1998)

$$F_t(t) = K_t \cdot a_{dc} \cdot t_c(t) \quad \text{and} \quad F_r(t) = K_r \cdot F_t \tag{2}$$

where K_t and K_r, the tangential and radial specific cutting constants which are dependent on the tool material for any geometry, a_{dc}, the axial depth of cut and, $t_c(t)$, the chip thickness, obtaining the cutting forces in Cartesian coordinates (Balanchandran, 2001). The most critical variable in the equation of motion, the chip thickness, $t_c(t)$, consists of a static part and a dynamic one. The static's is proportional to the feed rate and it is attributed to the rigid body motion of the cutter. The dynamic one models two subsequent passes of the tool through the same part of the work-piece. The phase shift between two consecutive passes of one tooth on the working-piece