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Adaptive controller design for feedrate maximization of machining process

F. Cus, U. Zuperl*, E. Kiker, M. Milfelner
Faculty of Mechanical engineering, University of Maribor,
Smetanova 17, 2000 Maribor, Slovenia
* Corresponding author: E-mail address: uros.zuperl@uni-mb.si

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Analysis and modelling

ABSTRACT

Purpose: An adaptive control system is built which controlling the cutting force and maintaining constant roughness of the surface being milled by digital adaptation of cutting parameters.

Design/methodology/approach: The paper discusses the use of combining the methods of neural networks, fuzzy logic and PSO evolutionary strategy (Particle Swarm Optimization) in modeling and adaptively controlling the process of end milling. An overall approach of hybrid modeling of cutting process (ANfis-system), used for working out the CNC milling simulator has been prepared. The basic control design is based on the control scheme (UNKS) consisting of two neural identificators of the process dynamics and primary regulator.

Findings: The experimental results show that not only does the milling system with the design controller have high robustness, and global stability but also the machining efficiency of the milling system with the adaptive controller is much higher than for traditional CNC milling system. Experiments have confirmed efficiency of the adaptive control system, which is reflected in improved surface quality and decreased tool wear.

Research limitations/implications: The proposed architecture for on-line determining of optimal cutting conditions is applied to ball-end milling in this paper, but it is obvious that the system can be extended to other machines to improve cutting efficiency.

Practical implications: The results of experiments demonstrate the ability of the proposed system to effectively regulate peak cutting forces for cutting conditions commonly encountered in end milling operations. The high accuracy of results within a wide range of machining parameters indicates that the system can be practically applied in industry.

Originality/value: By the hybrid process modeling and feed-forward neural control scheme (UNKS) the combined system for off-line optimization and adaptive adjustment of cutting parameters is built.

Keywords: Artificial intelligence methods; Machining; Force control; Adaptive control with optimisation

1. Introduction

The use of computer numerical control (CNC) machining centers has expanded rapidly through the years. A great advantage of the CNC machining center is that it reduces the skill requirements of machine operators. However, a common drawback of CNC end milling is that its operating parameter such as spindle speed or feedrate is prescribed conservatively either by a part programmer or by a relatively static database in order to preserve the tool.

As a result, many CNC systems run under inefficient operating conditions. For this reason, CNC machine tool control systems, which provides on-line adjustment of the operating parameters, is being studied with interest. These systems can be classified into three types: a geometric adaptive compensation (GAC) system; an adaptive control optimization (ACO) system; and an adaptive control constraints (ACC) system. GAC systems enhance part precision by applying real time geometric error compensation for imprecision caused by varying machine temperature, imprecise machine geometry, tool wear and other factors [1]. However, due to the difficulty in on-line measurement of tool wear and machine tool temperature, there are no commercial GAC systems available [2].

ACO systems and ACC systems enhance productivity by applying an adaptive control technique to vary then machining variables in real time [3]. ACO systems set up the most effective cutting condition for the present cutting environment. For this purpose, ACO systems require on-line measurement of tool wear

Unfortunately, adaptive control alone cannot effectively control cutting forces. There is no controller that can respond quickly enough to sudden changes in the cut geometry to eliminate large spikes in cutting forces. Therefore, we implement on-line adaptive control in conjunction with off-line optimization.

In our AC system, the feedrate is adjusted on-line in order to maintain a constant cutting force in spite of variations in cutting conditions.

2. System for off-line optimization and adaptive cutting force control

The overall force control strategy consists of optimizing the feedrates off-line, and then applying on-line adaptive control during the machining process. The basic idea of this design is to merge the off-line cutting condition optimization algorithm and adaptive force control (Figure 1). Based on this new combined control system, very complicated processes can be controlled more easily and accurately compared to standard approaches. The objective of the developed combined control system is keeping the metal removal rate (MRR) as high as possible and maintaining cutting force as close as possible to a given reference value.

Sequence of steps for on-line optimization of the milling process is presented below.

1. The recommended cutting conditions are determined by ANfis (adaptive neuro-fuzzy inference system) models, which are basic elements of the software for selecting the recommended cutting conditions.
2. Optimization of recommended cutting conditions by PSO optimization.
3. The pre-programmed feed rates determined by off-line optimization algorithm are sent to CNC controller of the milling machine
4. The measured cutting forces are sent to neural control scheme,
5. Neural control scheme adjusts the optimal feedrates and sends it back to the machine,
6. Steps 1 to 3 are repeated until termination of machining

The adaptive force controller adjusts the feedrate by assigning a feedrate override percentage to the CNC controller on a 4-axis Heller, based on a measured peak force (see Figure 1). The actual feedrate is the product of the feedrate override percentage (DNCFRO) and the programmed feedrate. If the software for optimization of cutting conditions was perfect, the optimized feedrate would always be equal to the reference peak force. In this case the correct override percentage would be 100%.

A CNC milling simulator is used to evaluate the controller design before conducting experimental tests. The CNC milling simulator tests the system stability and tunes the control scheme parameters. The simulator consists of a neural force model, a feed drive model and model of elasticity.

The neural model predicts cutting forces based on cutting conditions and cut geometry as described by Zuperl [4] and Tarng [5]. The feed drive model simulates the machine response to changes in desired feedrate. The elasticity model represents the deflection between the tool and the workpiece. Model is adapted from [4]. The system elasticity is modeled as static deflection of the cutter.

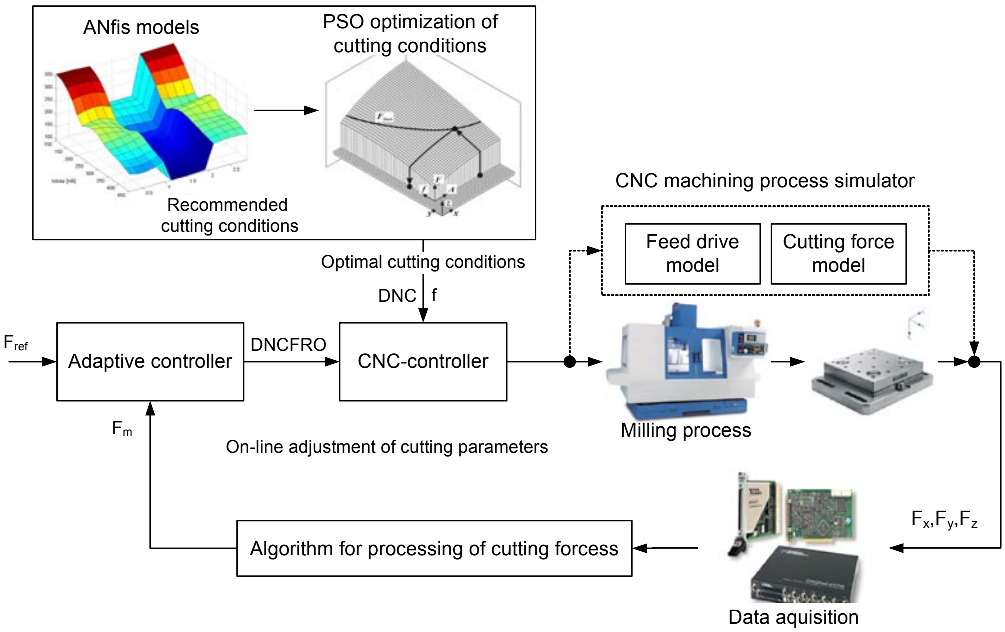

Fig. 1. Feedrate override percentage in closed loop system

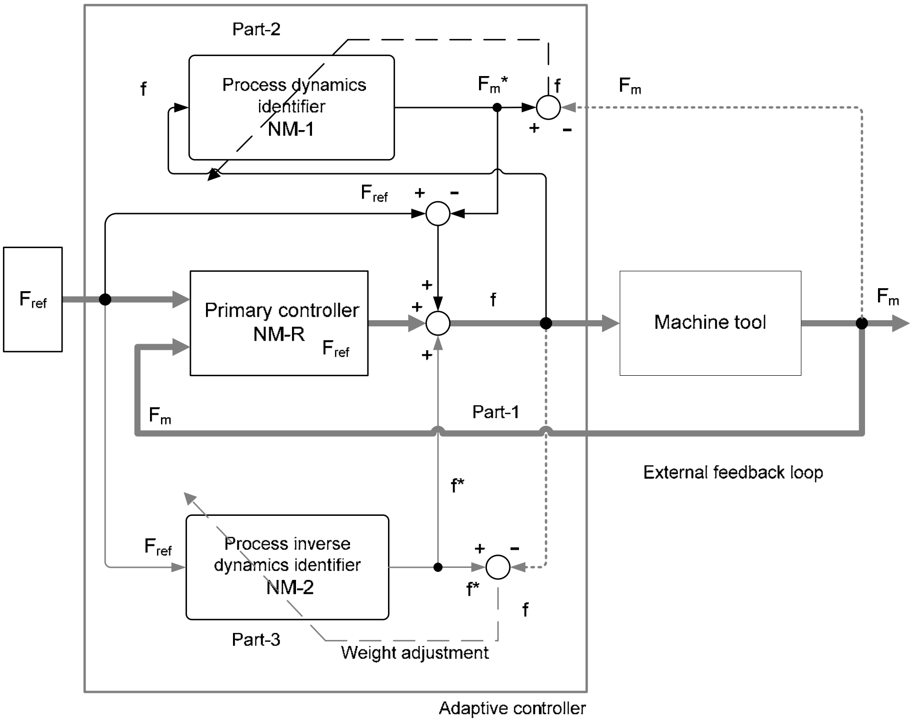

Fig. 2. Feed-forward neural control scheme (UNKS)

3. Self- learning control scheme

The fundamental control principle is based on the Feed-forward neural control scheme (UNKS) consisting of three parts (Figure 2). The first part is the loop known as external feedback (conventional control loop). The feedback control is based on the error between the measured (F_m) and desired (F_{ref}) cutting force. The primary feedback controller is a neural network (NM-R) which imitates the work of division controller. The second part is the loop connected with neural network 1 (NM-1), which is internal model of process dynamics. It acts as the process dynamics identifier. The third part of the system is neural network 2 (NM-2). The NM-2 learns the process inverse dynamics. The UNKS operates according to the following procedure. During the learning stage, NM-2 learns the inverse dynamics. As learning proceeds, the internal feedback gradually takes over the role of the external feedback and primary controller. The final result is that the plant is controlled mainly by NM-1 and NM-2. This is an adaptive control system controlling the cutting force and maintaining constant roughness of the surface being milled by digital adaptation of cutting parameters.

4. Experimental testing of adaptive control system

To examine the stability and robustness of the proposed control strategy, the system is first analysed by simulations using LabVIEW´s simulation package Simulink [4]. Then the system is verified by experiments on a CNC milling machine (type HELLER BEA1) for Ck 45 and16MnCrSi5 XM steel workpieces with variation of cutting depth (prismatic workpiece profile, see Figure 3.

Feedrates for each cut are first optimized off-line, and then machining runs are made with controller action. The ball-end milling cutter (R216-16B20-040) with two cutting edges, of 16 mm diameter and 10° helix angle was selected for experiments [6]. Cutting conditions are: milling width R_D=3 mm, milling depth A_D=2 mm and cutting speed v_c=80 m/min.

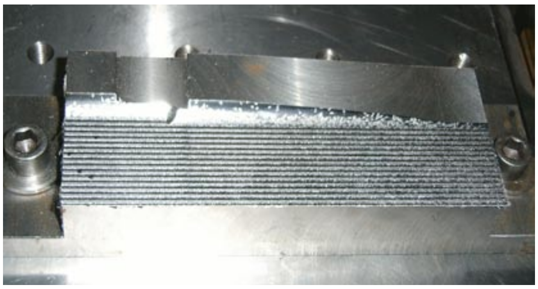

Fig. 3. Prismatic workpiece

The parameters for adaptive control are the same as for the experiments in the conventional milling. To use the structure of combined system on Figure 1 and to optimise the feedrate, the desired cutting force is [F_{ref}] =280 N, pre-programmed feed is 0.08 mm/teeth and its allowable adjusting rate is [0 - 150%].

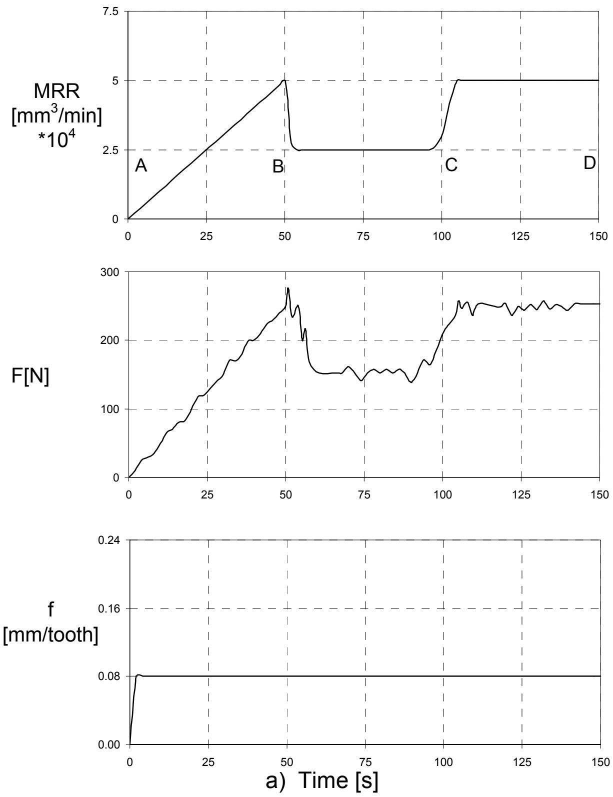

Fig. 4. Experiment-2; Machining of irregular profile by off-line optimizing of cutting conditions and adaptive adjusting of feedrate

5. Results and discussion

In the first experiment using constant feed rates (conventional cutting-Figure 4a) the MRR reaches its proper value only in the last section. However, in second test (Figure 4b), machining the same piece but using adaptive control, the average MRR achieved is much more close to the maximal MRR. Comparing the Figure. 4a to Figure 4b, the cutting force for the neural control milling system is maintained at about 250N, and the feedrate of the adaptive milling system is close to that of the conventional milling from point C to point D. From point A to point C the feedrate of the adaptive milling system is higher than for the classical CNC system, so the milling efficiency of the adaptive milling is improved. The experimental results show that the MRR can be improved by 27%.

6. Conclusions

On the basis of the cutting process modeling, off-line optimization and feed-forward neural control scheme (UNKS) the combined system for off-line optimization and adaptive adjustment of cutting parameters is built. This is an adaptive control system controlling the cutting force and maintaining constant roughness of the surface being milled by digital adaptation of cutting parameters. In order to check the applicability of the adaptive control algorithm, cutting experiments were carried out. The results show that the developed adaptive control algorithm has good stability as well as excellent applicability behavior.

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