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Surface roughness fuzzy inference system within the control simulation of end milling

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ABSTRACT

This paper presents a surface roughness control of end milling with associated simulation block diagram. The objective of the proposed surface roughness control is to assure the desired surface roughness by adjusting the cutting parameters and maintaining the cutting force constant. For simulation purposes an experimentally validated surface roughness control simulator is employed. Its structure combines genetic programming (GP), neural network (NN) and adaptive neuro fuzzy inference system (ANFIS) based models. Surface roughness control simulator simulates the surface roughness of the part by enabling the regulation of cutting force. The focus of this research is to develop a reliable method to predict surface roughness average during end milling process. An ANFIS is applied to predict the effect of cutting parameters (spindle speed, feed rate and axial/radial depth of cut) and cutting force signals on surface roughness. Machining experiments conducted using the proposed method indicate that using an appropriate cutting force signals, the surface roughness can be predicted within 3% of the actual surface roughness for various end-milling conditions. Simulation results are presented to confirm the efficiency of a control model.

1. Introduction

The machining cost on computer numerically controlled (CNC) machine tools is sensitive to the cutting parameters. Therefore, the proper selection of cutting parameters is an important step toward gaining a competitive advantage in the market [1]. In modern CNC systems, cutting parameters are usually selected conservatively before machining according to programmer's experience and machining handbooks. As a result, many CNC systems run under inefficient operating conditions. Due to above mentioned facts machine tool control systems which provide on-line adjustment of the operating parameters, are being studied with interest. To improve the efficiency, a trend toward equipping the CNC milling machine with modern control systems was noticed [2]. Most frequently that is materialised by measuring the cutting forces because they contain most information about the process and the tool condition. By analyzing the cutting force characteristics it is also possible to assess the changes of the quality of surface finish.

Since conventional controllers cannot guarantee system performance and stability as the machining process varies, a research effort has been invested in the development of adaptive force control systems, which provide on-line adjustment of cutting parameters. These adaptive systems can be classified into three types: a geometric adaptive compensation (GAC) system [3]; an adaptive control optimisation (ACO) system [4]; and an adaptive control constraints (ACC) system [5]. Due to required on-line measurements, only a few commercial GAC and ACO system are used in industrial environment.

The ACC systems are easier to design and implement than other adaptive systems. The ACC is the most effective technique of solving the above mentioned problem. ACC controls the cutting parameters to maintain the maximum working conditions during time varying milling process. The most commonly used constraint in ACC systems is cutting force. The operating parameter is usually feed rate. Their typical applications to constant cutting force control systems are described in [6]. The major ACC systems are based on the feedback control, self-tuning control, model reference adaptive control (MRAC), neural network (NN) and fuzzy control. The most frequently used adaptive system in machining is MRAC based ACC system [7]. It is widely used for its robustness and disturbance rejection capability. Many MRAC based ACC milling systems have been developed [8,9]. The purely empirical MRAC system was originally investigated by Landers [10]. The first application of the

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MRAC to milling operations was introduced by Tomizuka [11]. In recent years soft controllers based on artificial intelligence (AI) have earned attention. Cerebelar model articulation controller (CMAC) [12] and multilayered NN controller [13,14] have played important roles in research of neural control of machining. The NN based MRAC system [15] allow much faster development of the models and thus make these controllers practical.

No research efforts have been dedicated so far in milling to develop MRAC system which is based on combinations of different AI methods.

Unfortunately, adaptive control alone cannot effectively control surface finish. There is no controller that can respond quickly enough to sudden changes in the cut geometry to eliminate large spikes in surface roughness.

Therefore in this research, off-line cutting condition optimisation module is merged with surface roughness control. The off-line optimisation is performed with Particle Swarm Optimisation (PSO) algorithm developed by Zuperl [16]. An adaptive neuro fuzzy inference system (ANFIS) is used to obtain the relation between surface roughness, cutting parameters and cutting force. Then based on this modelled relationship the model based surface roughness control is developed. This is an adaptive control system for milling with a cutting force constraint. It modifies the feed rate and spindle speed to keep the surface roughness constant. Its structure is presented in Section 1.

The efficiency of the surface roughness control is tested by series of simulation. For simulation purposes a novel surface roughness control simulator of end milling is developed and presented in Section 3. It consists of a reference force model, control model, CNC milling simulator and ANFIS surface roughness prediction model. The ANFIS is used to effectively predict the surface roughness.

Indeed, several others models have been developed to predict the surface roughness. These include classical statistical approaches [17,18] as well as fuzzy systems [19], NN [20,21] and genetic algorithms [22,23]. A few NN based surface roughness prediction models have been proposed, but in these models the nonlinear relationship between cutting force signals and surface roughness embedded in a NN remains hidden to the user [13]. This is the main reason why ANFIS has been used in this research to predict the surface roughness. After training the ANFIS, its performance was tested under various cutting conditions. Recently, some others ANFIS based surface finish prediction models have been presented [24,25]. However, none of these works have addressed finding the optimal rule base of ANFIS model, and furthermore some predictive values have great errors (nearly 14%) in [25].

2. Surface roughness control

The idea of this research is to merge the off-line cutting condition optimisation module with the genetic programming (GP) and the ANFIS model based surface roughness control (Fig. 1). The objective of the proposed surface roughness control is therefore to adjust the milling cutting parameters and maintain the cutting force constant to achieve on-line the desired value of the surface finish. If the cutting force is maintained constant during the process of machining process, then the surface finish also remain stable. The control model adjusts the feedrate and spindle speed by assigning an override percentage to the CNC controller on a 3.5-axis Heller, based on a measured resultant cutting force. The control model consists of a feed rate control model M2 and a spindle speed control model M3 (Fig. 2). The actual feedrate is the product of the feedrate override percentage (DNCFRO) and the programmed feedrate. The actual spindle speed is the product of the spindle speed override percentage (DNCSPO) and the programmed spindle speed. If the software for optimisation of cutting parameters was perfect, the optimised feedrate would always result in the machining operating at desired surface roughness. In this case the correct override percentage would be 100%.

In order for the control model to regulate surface roughness, force information must be available to the control algorithm at every controller sample time. The data acquisition software (Labview) is employed to provide maximum (peak) cutting force information to the control model at each sample time. A variety of simulations revealed that the limiting factors in selecting a sample time are machine tool-feed drive response time and spindle speed. The sample time must be longer than the machine settling time to a change in a commanded feed rate or spindle speed. A controller sample time of 20 ms was found by simulations to give good results. The sampling cycle of cutting force is 1 ms and the control cycle of the feed rate/spindle speed is 20 ms. The cutting force resultant is obtained using a Kistler force dynamometer, which provides of three orthogonal components of dynamics forces. These measured cutting force signals are used in the control model to regulate the cutting force and to predict the final roughness average R_a.

Sequence of steps for surface roughness control of end milling is presented below:

1. The optimised feed rates and spindle speeds determined by the off-line optimisation module are sent to the CNC controller of the machine tool,
2. The desired value of surface roughness $R_{a\ d}$ is initiated,
3. Based on $R_{a\ d}$ the reference force F is predicted according to the GP reference force model M1 (Fig. 1),
4. When the force F is known, the feed rate velocity command f_c and spindle speed velocity command n_c is determined according to the control model,
5. The measured cutting forces are compared with reference value and sent to the control model,
6. The final surface roughness average R_a is predicted and displayed according to the ANFIS model M5. The inputs to the model are cutting parameters and measured cutting force,
7. The control model adjusts the feed rates and spindle speeds and sends them back to the CNC controller,
8. Steps 5 to 7 are repeated until termination of machining.

2.1. Off-line optimisation module

The basic idea of this optimisation approach is to merge the PSO algorithm and NN based cutting force model. The architecture of the system is developed by Zuperl [16].

The optimisation process executes in two phases. In first phase, the cutting force model generates 3D surface of cutting force, which represent the feasible solution space for the PSO algorithm. The output of the cutting force model is fed into the multi-objective particle swarm optimiser where the constraints are defined. PSO algorithm generates a swarm of particles (optimum solution candidates) on the cutting force surface during the second phase. Swarm of particles flies over the cutting force surface and searches for maximal cutting force. The coordinates of a particle which has found the maximal (but still allowable) cutting force represent the optimal feed rate and spindle speed.

3. Surface roughness control simulator

By replacing the machining process (machine tool and the cutting force dynamometer) in surface roughness control scheme on Fig. 1 with the CNC milling simulator, an effective surface roughness control simulator is obtained (see, Fig. 2). The purpose of this simulator was to analyse the efficiency of the control model without expensive and time consuming machining tests. The surface