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Fuzzy-logic control of cutting forces in CNC milling processes using motor currents as indirect force sensors

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ABSTRACT

A fuzzy-logic controller (FLC) is designed to automatically adjust feed rate in order to regulate the cutting force of milling processes in a vertical machining center. The FLC has a double-loop structure, consisting of the inner PD (proportional-derivative) velocity-control loop for a feed servo and the outer fuzzy-logic force-control loop. Reference cutting forces are well maintained in both numerical simulation and experiments when the cutting-depth profile of an aluminum workpiece (Al6061-T6) is varying step-wise or continuously. In order to replace expensive and impractical tool dynamometers, ac-induction-motor currents in the feed system and the spindle system are analyzed, and then compared as a cutting-force sensor. The bandwidth of both systems are not high enough to sense the cutting dynamics for common spindle speeds. Thus, quasi-static quantities (i.e., average or maximum resultant cutting force per spindle revolution) are compared instead. The spindle-motor current is chosen because quasi-static sensitivity is much higher (i.e., 5.415×10^{-3} vs. 2.128×10^{-4} A/N). Reference cutting forces (230 and 330 N) are well maintained when the depth of cut is less than 4 mm.

1. Introduction

Process control of CNC-aided machine tools is used to maximize productivity while maintaining part quality and integrity of machine tools [1]. However, process controls such as control of chatter, cutting force, and tool condition, have not been fully integrated into commercial machine tools even after decades of research and development [2]. The difficulties include a lack of affordable and accurate process-monitoring tools, and robust control algorithms that can cope with complex, nonlinear, time-varying and sometimes unpredictable machining processes.

In machining, a high metal-removal rate (MRR) is an important factor that determines productivity. However, the cutting parameters (i.e., spindle speed and feed rate) are usually set at a constant value in a conservative manner. Or a skilled technician constantly monitors machining processes and modifies cutting parameters to prevent excessive machining forces from causing machine-tool damage. As a result, it is difficult to maximize productivity when effective process monitoring and control are not available.

Automation of machining processes using ACC (adaptive control with constraint), in which the machining parameters are adjusted in real time to have adequate process variables, has been studied [2]. Maintaining machining forces at a maximum allowable level by automatically controlling cutting parameters results in improvement of productivity [3]. Model-based control algorithms have been studied extensively. Fixed-gain control was not effective [4] due to dynamically varying model parameters which depend on cutting parameters [1]. Thus, adaptive control was introduced to account for changes in the model parameters over time [4–8]. Control algorithms robust to a range of parameters or model variations were also studied recently [9–12]. However, all of these approaches have not lived up to industry expectations, mainly because of the lack of accurate models for complex and nonlinear machining dynamics, and tremendous inherent variation of force processes [13].

Fuzzy-logic control, an artificial-intelligence-based method, is a viable alternative to model-based control schemes. Skilled human operators are shown to be better than model-based controllers in machining control [14]. The human experience can cope with uncertainty and complexity of machining process successfully [15]. Human operators express the process variables in “imprecise” language (i.e., linguistic variables) and apply them to the control of machine tools. A lack of accurate models, model parameters, and exact numerical values of machining conditions is not a problem. Thus, human-based methods of obtaining control outputs (i.e., cutting parameters) can be adapted to the constant-force control that maximizes MRR. Fixed-rule fuzzy controllers [15,16] and

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learning-capable fuzzy schemes [17,18] have been studied, and implemented on milling processes.

The cutting forces of a milling process are usually measured with a table-mounted tool dynamometer in research laboratories. A dynamometer is expensive, axis travels are limited, and cutting fluid can damage the dynamometer [19]. As a result, dynamometers are not widely used in the industry. Thus, much effort has been devoted to developing indirect force-measurement tools.

Various mechanical or electrical variables of feed- and spindle-system conditions have been studied to estimate forces. For spindle systems, Shuaib et al. [20] installed a strain gauge between the spindle axis and the tool, and then measured cutting torque. It is advantageous to measure the cutting force at a spindle because it is close to the cutting point. However, complexity of spindle integration is problematic. The space for installation is limited in many spindle systems without significant modification [21]. Wiring of the sensor installed at the rotating spindle is not simple. Shuaib et al. used a garter-spring pickup for signal transmission. Electrical noise and abrasion due to the constant contact render this approach unreliable. More modern torque measurement based on piezo-quartz transducers (i.e., rotating dynamometer) transmits signal wirelessly, but this device is also very expensive, requires special tooling, makes it difficult to use tool changer, and changes process dynamics. Bertok et al. [22] predicted a spindle-motor torque using an empirical equation of MRR and workpiece-tool contact area. The spindle current, that was calibrated with a dynamometer, was used to identify parameters of the equation. The average cutting torque was predicted off-line using the equation, solid models of workpiece material and tool, and NC data for tool path. This approach may provide a rough guide for parameter settings prior to actual machining, and can be used as a tool condition monitoring if the measured torque is far off the predicted value. It may not be appropriate as an alternative sensor for real-time cutting-force control because there is no mechanism to compensate an unavoidable discrepancy between the predicted and measured torque (e.g., tool wear, inaccurate solid model, axis misalignment, workpiece flatness error). Also, using maximum torque information is better than using average torque of their work in preventing machine-tool damage.

Current and power of motors in a machine tool have been studied as an alternative sensor. As current and power are variables describing electromechanical systems (i.e., feed and spindle axes), the system dynamics must be identified prior to the use of sensor. These electromechanical systems act as a low-pass filter, so that the bandwidth of sensor is low compared to a dynamometer. The power consumed by cutting processes is usually a small portion of the total power that a feed or spindle system requires, so they are generally less accurate [21]. Nevertheless, current and power are attractive for industrial applications. These methods are possibly the most easily accessible variables. Additionally, current and power sensors are very cheap compared to dynamometers. It is easy to install sensors with simple retrofitting, and even some motor drives have built-in current readings. Current and power measurement does not obstruct machining processes. Stein and Wang [23] used a current sensor (i.e., hall-effect current transducer) and voltage transformer to obtain spindle-power consumption in a milling machine. Then the cutting torque was estimated using the rotor input power and synchronous speed measured with an optical shaft encoder. For feed systems, Altintas [24] measured the dc-motor currents of feed drives in a vertical milling machine. Stein et al. [25] characterized the dc-motor current of the feed system in a CNC lathe. Lee et al. [26] used the ac-motor currents to predict the cutting forces in an NC milling machine. Mannan and Broms [27] also used a setup similar to Stein and Wang. They used the spindle power to calculate cutting torque, and feed motor currents to obtain feed force in turning, milling, and drilling operations. For all these cases, the correlation between current/power and cutting force/torque are preidentified using a dynamometer.

In this study, currents of an ac-induction motor for both the feed and spindle systems are compared in terms of sensitivity and bandwidth to assess their applicability to fuzzy-logic-based cutting-force control of a milling process. To our knowledge, there has been no attempt to compare both the currents as an alternative force sensor for this purpose. After the comparison, the spindle motor current is selected due to its superior performance. The design procedure of the cutting-force controller is as follows: (1) A mathematical description of cutting forces in x and y axes was derived, and verified using actual cutting-force data measured with a dynamometer (2) A servo controller for y-axis feed and the FLC for cutting-force regulation are designed. (3) The numerical simulation based on the cutting-force model, and machining experiments are performed to verify whether the FLC successfully maintains a constant force by adjusting the feed rate in real time for varying depth of cut. (4) Motor currents of feed and spindle systems are characterized in terms of sensitivity and bandwidth using a mathematical model and cutting-force data. (5) The cutting force is estimated using the spindle-motor RMS (root-mean square) current, and using the predetermined relationship between the current and cutting force measured with a tool dynamometer. Milling experiments with varying depth of cut are performed to verify the proposed force-control system.

2. Experimental apparatus

2.1. Machine tool

A vertical machining center, ACE-V30 (Daewoo Heavy Industries, Incheon, South Korea), equipped with a built-in controller (System 100M, Korea Industrial Electronics Co., Ltd., Seoul, South Korea) was used in this work. Two-flute flat-end mills (YG-1 Co. Ltd., Incheon, South Korea) were used for cutting experiments. Diameters of the end mills were 8, 10, and 12 mm.

2.2. Workpiece material

Workpiece material was Al6061-T6 aluminum. Aluminum blocks were machined to have multiple steps of depth of cut or a linearly varying depth of cut using the built-in controller and simple G codes.

2.3. Dynamometer

A tool dynamometer (Model 9257B, Kistler Instrumente AG, Winterthur, Switzerland) was mounted on the table of the ACE-V30. The dynamometer has multiple quartz-based piezoelectric force transducers in a steel housing. When force is acting on the dynamometer, each transducer produces a charge proportional to the force component sensitive to that axis. The 9257B model measures force in x, y, and z axes (no torque measurement). The charge is then converted into voltage signal using a multi-channel charge amplifier (Model 5019A, Kistler). The measuring range is ± 5 kN. Sensitivity is -7.5 pC/N for x and y axes and -3.7 pC/N for z axis. Force data in voltage signal are sampled at 1 kHz with a DAQ (data acquisition) board (Model DS2201, DSPACE Inc., Wixom, MI, USA).

2.4. Current sensor

A 9-channel current-sensor board made in-house, was installed in the electrical cabinet to measure motor currents of feed and spindle systems. Hall-effect current transducers (LX-10, Nana Electronics, Tokyo, Japan) on the board convert 3-phase current outputs