A Control Scheme for Grinding Based on Combination of Fuzzy and Adaptive Control Techniques

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Abstract

This paper presents a control system for grinding process using a combination of fuzzy control and adaptive control techniques. For lacking of ability to self-tuning, the behavior of traditional grinding tool is largely dependent on the experience and skills of its operator. Here, due to the complexity of the grinding process and the difficulty in modeling, corresponding fuzzy control method is put forward. Considering the contradiction between productivity and quality, an adaptive controlled optimization (ACO) is proposed. In addition, an example of how to avoid workpiece burn in final grinding process is taken in this paper. And simulation based on above example is carried out. The simulation results show that the method developed in this paper is effective.

Keyword: Fuzzy control; Adaptive control; Grinding; Thermal damage.

I. Introduction

Grinding is one of the most versatile methods of removing material from machine parts to provide precise geometry [1]. However, little attention has been paid to the grinding process, which is usually the last finishing process of a high-precision component in the manufacturing industries. So results such as low roughness, dimensional and shape error control, optimum tool-life, with minimum cost and time are desired. Damages on the parts are very expensive since the previous processes and the grinding itself are useless when the part is damaged in this stage. Thus, it is necessary to design a proper intelligent control system for the grinding process. The selection of grinding parameters is determined by the technological and economic considerations. Now, there is a vast body of theoretical and empirical information in the literature to assist process planners to select the cutting parameters for grinding operations. In this way, the machining cost and product quality are largely dependent on the experience and skills of its operator. Numerous control system studies of grinding processes have been carried out in the last decades, e.g. control of ball mill grinding circuit using model predictive control scheme by M. Ramasamy[2], neural modeling control and optimization of an industrial grinding process by James J. Govindhasamy[3] and a fuzzy model for predicting burns in surface grinding of steel by L.C. Zhang[4] and so on. However, little attention has been paid to develop a knowledge-based and empiricism-based systemic grinding control scheme which allow for efficient selection of cutting parameters based directly on the work and cutting tool material properties by itself. Here, a new control strategy is proposed. It utilizes fuzzy controller to make sure the grinding process in working order. Furthermore, it utilizes self-adaptive controller to judge the work state of this system, optimize grinding parameters. Meanwhile, how to avoid the workpiece burn in final grinding process and ensure material removal rate (MRR) close to the maximum under this control system is also introduced.

The rest of this paper is organized as follows. In section 2, the control scheme for the complex grinding process is proposed. A detail design of control scheme is introduced in section 3. The control system is simulated under Matlab6.5.1 environment and the simulation results of the control scheme are presented in Section 4. In the last Section, a conclusion about simulation results and a discussion about possible further work are given.

II. Control Scheme

Grinding operation is complex since it is characterized by a number of design parameters and variables such as grindability of the raw materials, particle size distribution, material hold-up, and rotational speed of the wheel, etc. The general lack of sensors in industrial plants makes the investigation of the several material grinding and transportation mechanisms inside the mill particularly delicate, or even impossible. The complexity of system and the difficulty to observe internal phenomena do not allow a thorough knowledge of the grinding process. In this way, perhaps it is reasonable to apply a knowledge-based and empiricism-based fuzzy controller in such complex grinding process. On the other hand, a production operation does not require an “absolute” model that can deliver extreme accuracy, because such accuracy is not reproducible in practice. What is needed, as pointed out by Shaw [5], is a “relative” model that can guide the user generally as to what to do and how to do. This is because there will always be a certain degree of on-shop trial-and-error, but a relative model will make a good starting point. By now, numerous modeling about grinding processes have been worked out, e.g., the lumped parameter models proposed by Austin et al. [6] the distributed parameter models developed by Horst [7] and the grinding force models and thermal models are also developed by S. Malkin [8]. Based on these previous works, a knowledge-based and empiricism-based fuzzy control model is possible to be built. However, there are still some unknown parameters needed to get in fuzzy models and minimum machining cost and precise geometry are expected at one time. In this way, the methods of parameters estimation and self-tuning regulator are utilized. Finally, the control scheme is built (shown in Figure 1). It utilizes fuzzy controller obtained by knowledge-based and empiricism-based data to make sure the grinding process work in order.

Furthermore, it utilizes self-adaptive controller to judge the work state of this system, optimize grinding parameters.

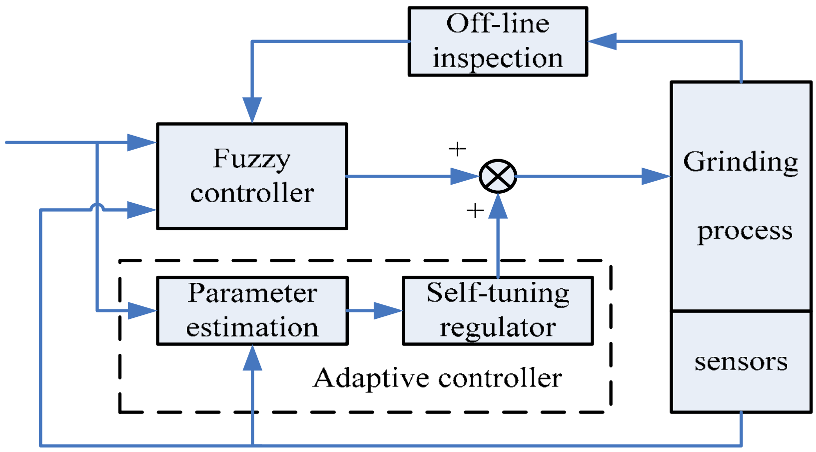


Figure1. Control block diagram of grinding system.

III. Control System Design

Firstly, it is necessary to introduce some knowledge about grinding for understanding. In this paper, it is limited to conventional grinding but not creep feed grinding. And conventional grinding is characterized by grinding with small depth of cut and high work speed. The grinding processes consist of three stages: sliding stage, plow stage and chip-formation stage. The grinding processes are particularly energy-consuming. According to the three stages, the corresponding specific grinding energy (u) composes of sliding energy (u_{sl}), plow energy (u_{pl}) and chip-formation energy (u_{ch}). Experiment shows that the chip-formation energy is close to constant. In addition, the machining parameters mentioned later in this paper are circumferential speed of a grinding segment (v_s), workpiece velocity (v_w) and table speed (f) depth of grinding (a) etc. For more information please peruse [8] by S. Malkin. Next, we shall introduce each of the components of the control system by means of a simple problem of how to avoid workpiece burn on grinding machine tool MM7150A in final grinding process.

A. Fuzzy Controller

A block diagram of a fuzzy controller is shown in Figure2, which is composed of the following four elements:

a) A rule-base, which contains a fuzzy logic quantification of the expert`s linguistic description of how to achieve good control.
b) An inference mechanism, which emulates the expert`s decision making in interpreting and applying knowledge about how best to control the plant.
c) A fuzzification, which converts controller inputs into information that the inference mechanism can easily use it to activate and apply rules.
d) A defuzzification, which converts the conclusions of the inference mechanism into actual inputs for the process.

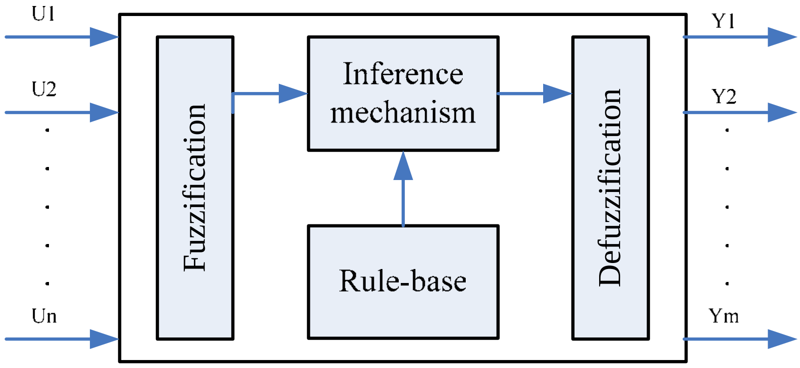


Figure2. Fuzzy controller

In this particular case of avoiding work-piece burn in final grinding process, the fuzzy controller is composed of two fuzzy models, by one of which the initial process parameters are inferred according to the empirical rules, and by the other one the values to correct the prior process parameters are worked out according to the inputs. Fuzzy models are built based on the following aspects:

a) Not any mild degree of surface burns can be tolerated during final grinding process.
b) From an iron-carbon phase diagram, it can be seen that the only constant independent of alloying is the eutectoid temperature (725℃). Therefore, surface burns can be considered to occur when the grinding temperature is higher than the eutectoid temperature, and when the duration is long enough for austenite formation to occur.
c) A bit hard of wheel grade tends to obtain fine dressing, but too hard wheel grade will result in work-piece burns.
d) The finer surface finish needs finer grit size.

For fuzzy modeling, all numeric values are replaced with linguistic values. Wheel Grade application is already linguistic ‘soft’, ’medium’ or ‘hard’. The other three numeric variables are fuzzified in a similar manner, by means of membership functions. Especially, circumferential speed of a grinding segment (v_s) is close to constant for grinding machine tool MM7150A, the parameters of work-piece velocity (v_w) and depth of grinding (a) are input parameters of the grinding process. So they are outputs of the fuzzy controller. On the other hand, in the case of avoiding work-piece burn the parameters of machining temperature and its change ratio are very important. Thus they act as the input parameters in this fuzzy controller.

At last, we can develop the fuzzy models after consulting interrelated literatures [1], [8] and manual [9]. Under the Matlab6.5.1 environment the fuzzy control surfaces are also obtained (shown in Figure3). In these figures, *Theta* is the difference between machining temperature and desired temperature. *Dtheta* is the changing ratio of difference. Considering the undulation of the *Theta* will make *Dtheta* more undulatory, so here define *Theta* as the mean value of the error in 3 seconds and *Dtheta* as the mean value of the changing ratio in 6 seconds.

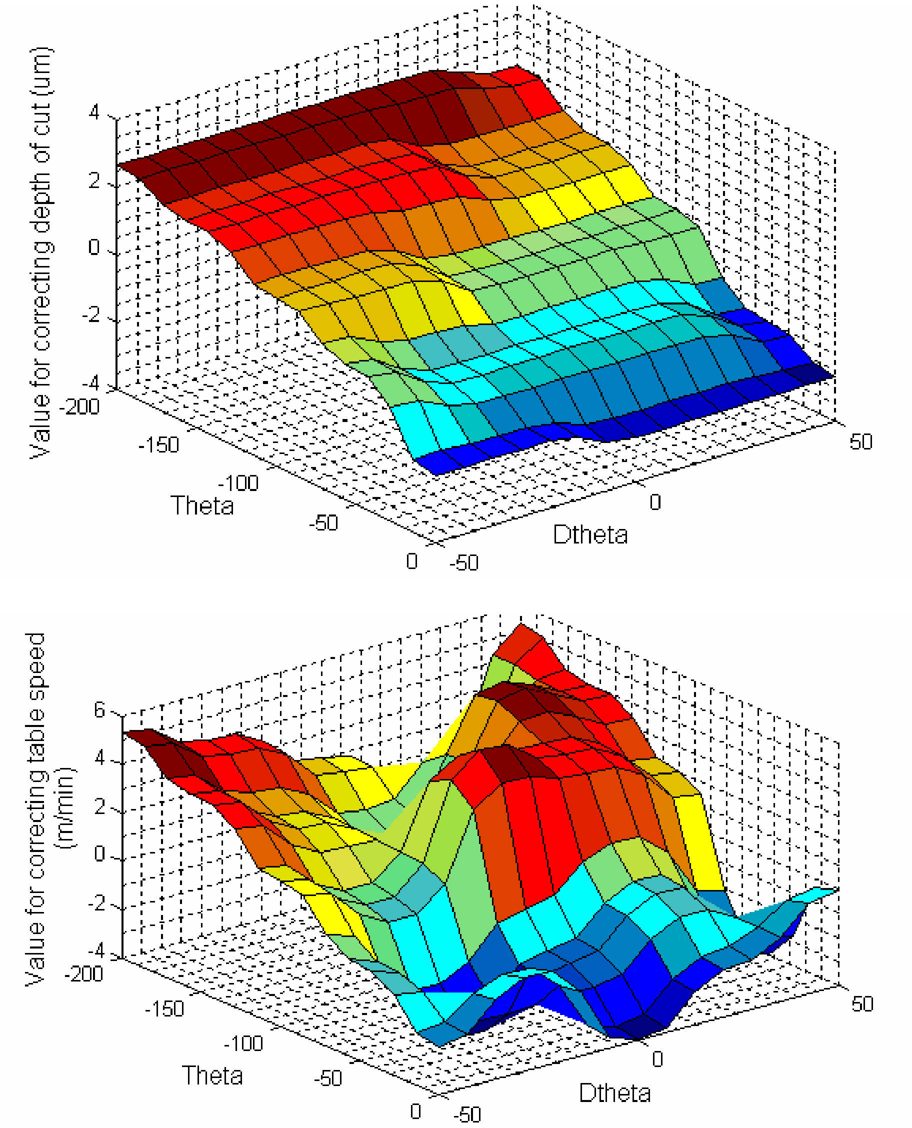


Figure 3. Control surfaces for correcting parameters.

B. *Adaptive Controller*

Two grinding parameters a and v_w are obtained by fuzzy controller at t time, and define their neighbor field $U_1(a,\delta_1)$ and $U_2(v_w,\delta_2)$ at this moment. As long as the fuzzy control model is effective, we should be sure that the optimum parameters a and v_w belong to the field $U_1(a,\delta_1)$ and $U_2(v_w,\delta_2)$ at t time. The adaptive controller we are going to design is in charge of working out the optimum control laws minutely. In addition, according to [8] we know the empirical formula of maximum machining temperature is:

$$Q_m = \frac{1.13\alpha^{0.5} a^{0.75} v_w^{0.5} (u - 0.45u_{ch})}{k d_e^{0.25}} \qquad (1)$$

where Q_m is the maximum temperature, α the thermal conductivity, a the depth of grinding, v_w the workpiece velocity, u the specific grinding energy, u_{ch} the chip-formation energy, k

the thermal diffusivity, d_e the equivalent wheel diameter. In above formula (1), Q_m can be measured real-time, a, d_e and v_w are known. Define $U=(u-0.45u_{ch})$, so U, α, k are unknown parameters needed to be estimated.

The natural logarithm of both sides of the formula (1) is as follows:

$$lnQ_m - ln(\frac{1.13a^{0.75}{v_w}^{0.5}}{{d_e}^{0.25}}) = 0.5ln\alpha + lnU - lnk \quad (2).$$

Assume $Y = ln\frac{Q_m {d_e}^{0.25}}{1.13a^{0.75}{v_w}^{0.5}}$, $\varphi = (0.5 \quad 1 \quad -1)$, and $x = (\ln\alpha \quad \ln U \quad \ln k)^T$,

then formula (2) can be written in the form:

$$Y = \Phi x \quad (3)$$

According to the theorem of Recursive least-squares estimation (RLS) [10], we can yield:

$$x_{N+1} = x_N + K_{N+1}(y_{N+1} - \varphi^T{}_{N+1}\theta_N) \quad (4)$$

$$K_{N+1} = P_N\varphi_{N+1}(1+\varphi^T{}_{N+1}P_N\varphi_{N+1})^{-1} \quad (5)$$

$$P_{N+1} = P_N - P_N\varphi_{N+1}(1+\varphi^T{}_{N+1}P_N\varphi_{N+1})^{-1}\varphi^T{}_{N+1}P_N \quad (6)$$

in above formulas, $\varphi^T{}_{N+I} = (0.5 \quad 1 \quad -1)$, $P_N = [\Phi^T\Phi]^{-1}$. In this way, we can obtain the estimation

at *t* time:

$$\hat{x}_t = (\ln\alpha_t \quad \ln U_t \quad \ln k_t)^T \quad (7).$$

Then with $\hat{x}_t$ estimated by above formulas and define $Q_m = T^\circ C$, here $T^\circ C$ is given temperature for avoiding workpiece burn. Hence we can develop the following in equation:

$$\frac{1.13{\alpha_t}^{0.5}a^{0.75}{v_w}^{0.5}(u-0.45u_{ch})_t}{k_t {d_e}^{0.25}} \le T^\circ C,$$

which can be further expressed as:

$$a^{0.75}{v_w}^{0.5} \le \frac{k_t {d_e}^{0.25}}{1.13{\alpha_t}^{0.5}(u-0.45u_{ch})_t} T^\circ C \ \underline{\underline{\text{def}}}\ A_t \quad (8)$$

where A_t can be worked out . On the other hand, to keep the machine working with efficiency as high as possible and to make sure workpiece burn is not occurred at one time are expected. In other words, we should maximize *MRR* before subject to inequation (8). We know:

$$MRR = Bav_w \quad (9)$$

where *B* is the width of wheel.
Considering equations (8), (9) and each parameter`s available bound, we can obtain following equations:

$$\begin{cases} MRR = \max |Bav_w| \\ \text{s.t.} \quad a^{0.75} v_w^{\ 0.5} \le \mathrm{A_t} \\ \text{s.t.} \qquad a \in U_1(a,\delta_1) \\ s.t. \qquad v_w \in U_2(a,\delta_2) \end{cases} \qquad (10).$$

At last, solving above equations (10) we can work out the control laws shown as follows:

$$v_w^{\ *} = A_t^{\ 2} a_t^{\ *-3/2}$$

where $a_t^{\ *} = min\{a \in U_1(\mathrm{a}, \delta_1)\}$.

III. Simulation

Here a comprehensive simulation study has been carried out under Matlab6.5.1 environment. Due to the fact that the mathematic model of the grinding process is impossible to be built exactly, hence only control scheme is simulated here. The finished model for simulating is shown in Figure 4. The input and results of simulation are also plotted in Figure 5. It should be mentioned that the simulation is based on the following process conditions:

width of the wheel: 40mm;
grit size of the wheel: 80#;
wheel grade: K.

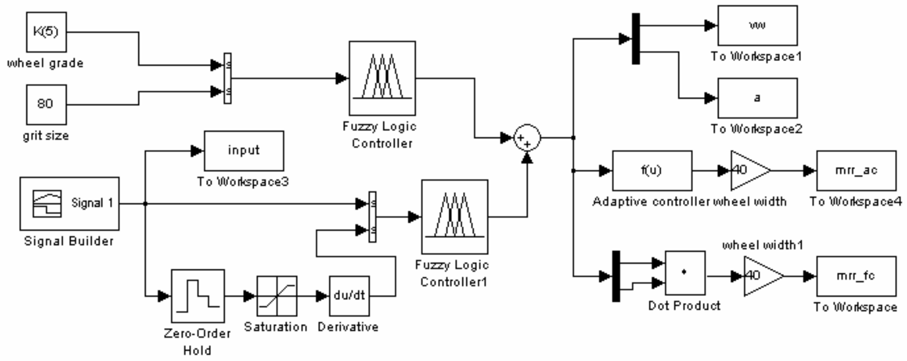
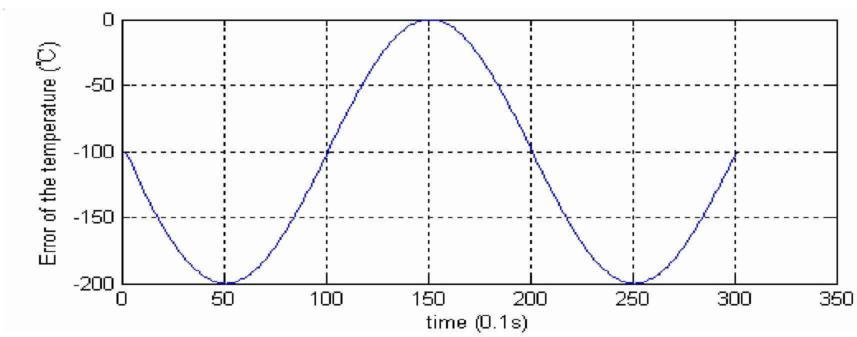
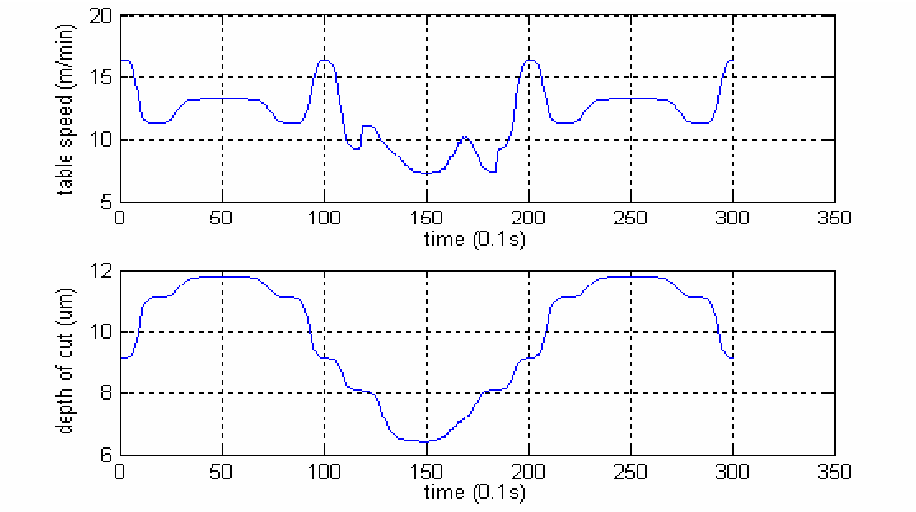


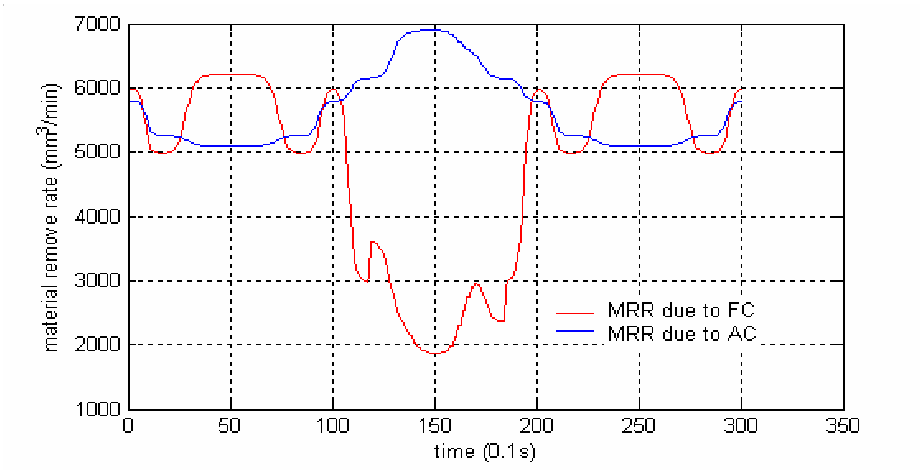
Figure 4. The model of the control scheme for simulating.



Input signal for simulating



Machining parameters worked out by fuzzy controller.



Comparison of MRR curve

Figure 5. The input and results of this simulation.

As it can be seen from above graphs, along with the changing of inputs, the obtained machining parameters are reasonable. In other words, the fuzzy controller is valid. Also, from the last figure, the comparison of the material removal rate curves due to the effects of fuzzy controller and adaptive controller shows that the latter behaves much smoother and has higher MRR than the former.

IV. Conclusions and Future Work

This paper developed a control scheme that combines fuzzy controller and adaptive controller. In addition, take an example of how to avoid workpiece burn in final grinding process to introduce the control system. At last, based on the simulation results, the following conclusions can be drawn:

a) The fuzzy controller can make grinding process in working order automatically.
b) This adaptive controller helps to improve MRR obviously.
c) As long as the control scheme is designed in reason, it is possible to meet the needs for low machining cost and high precision and accurate control of automated grinding process.

But in its current state, it is only limited to improving a certain part of performance. That is because there are still some challenges as follows in the way of working out an optimum control laws in terms of all-round performance specification.

a) The function for all-round performance specification is difficult to develop.
b) A proper and overall fuzzy control models for different grinding process are difficult to build.
c) Owing to the complexity of the grinding process, the time of computing the control laws has to be prolonged, as a result, adjustment parameters on-line is hard to realize currently.

Thus further research effort is still needed in the following stage to apply this control system in grinding machining tool.

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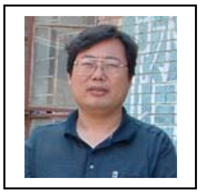

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