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HIGH SPEED AND HIGH PRODUCTIVE DRILLING BY INTELLIGENT MACHINE TOOLS
- Integration of the cutting conditions planning and adaptive control for drilling -

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ABSTRACT

This study aims to achieve total machining optimization by integrating the cutting conditions planning and adaptive control for drilling. The first question we have to ask here is how to determine the adequate cutting condition when drilling several workpieces, especially when the hardness of each workpiece is different and unknown. The proposed method determines the initial cutting condition based on the standard cutting characteristic for the material stored in the database, and identifies the cutting characteristics while cutting, then updates the identified cutting characteristics in the database.

Further more, a method to select an optimal adaptive control method among many candidates is proposed. This method estimates the performance index like cutting time based on the cutting process model before cutting, and selects the optimal adaptive control method.

The simulative case studies are also shown to prove the proposed method effective. In the first case study, supposing drilling the successive shallow holes for cast iron, the cutting time is reduced safely by about 40%. In the second case study, supposing the deep hole drilling for steel, the cutting time is reduced by about 5-20%.

INTRODUCTION

Nowadays a lot of high speed and high acceleration machining centers have been developed by many machine tools' builders. For effective use of this type machining centers, the intelligent machine tools was developed by the authors[1]. As the Fig.1 shows, the intelligent machine tools are equipped with the function to estimate the cutting force and cutting torque from the motor current signal, the adaptive control functions and the database that stores the suitable cutting conditions[2].

The term "adaptive control" refers to the adaptive control constraints that maximize the process variables (e.g. feed rate) subject to the given constraints (e.g. cutting force)[3]. The performance of the adaptive control on productivity depends mainly on the constraints, so little has been discussed about how to determine the adequate initial cutting conditions. Recently, cutting speed has been increased dramatically due to the advances of the cutting tools and machine tools. In many cases the cutting time becomes shorter than the adaptive control response time especially in drilling of some important car parts,

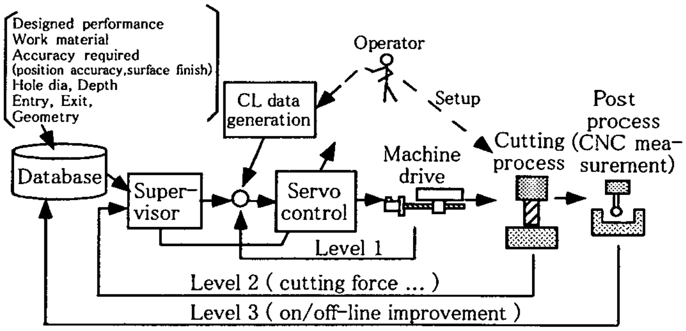


Fig.1 The concept of the intelligent machine tools

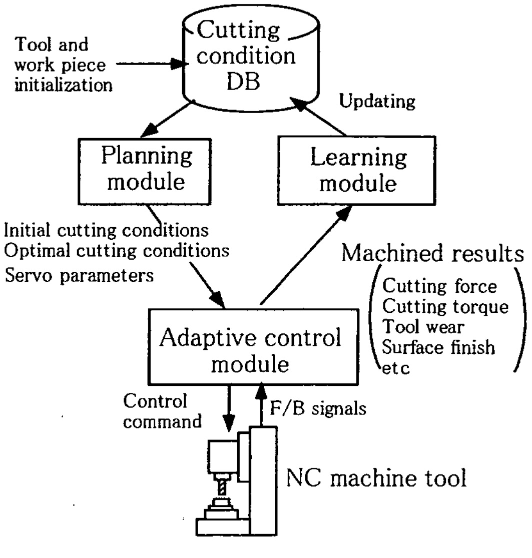


Fig.2 Data flow in intelligent machine tools including cutting condition database

such as cylinder blocks, cylinder heads and transmission cases. In such cases, to achieve the higher productivity, it is important to use adequate initial cutting condition, apart from tuning the constraints. This paper focuses on the determination of the adequate initial cutting condition taking the adaptive control behavior into consideration, especially when the cutting characteristics depending on the tools and workpieces are unknown. To this end, a method to determine the adequate initial cutting condition using identified cutting characteristics was proposed. This method measures the process data (e.g. cutting force) during machining and identifies the process parameters (relation between feed and cutting force/cutting torque) from the measured process data. The identified process parameters are used to update the database that is then used to determine the initial cutting condition for the next matching. This "learning cycle" optimizes the cutting condition for the material with unknown hardness(Fig.2).

In addition to that, it is quite important to select an adequate adaptive control method among many candidates to improve the productivity. Over the years, many adaptive control methods have been proposed[3]. Several researchers have proposed the adaptive control methods with multiple constraints corresponding objective line tool wear, tool breakage or accuracy[2,4,5]. But most of them are often effective only for the limited range of machining. This means that adequate adaptive method which suit each situation should be selected, especially for the machining centers, which are general purpose machine tools. Nevertheless, the question which adaptive control method should be selected when multiple adaptive control methods are available for the same objective has received little attention. To this end, a method to select an optimal adaptive control mode was proposed. This method estimates the performance like cutting time before cutting based on the cutting process model identified from the measured signal of the previous cutting.

Simulations were conducted to validate the proposed method. The simulation results show that the proposed method worked successfully.

CUTTING PROCESS MODEL

The adaptive control used here monitors the cutting thrust or cutting torque and controls the feed. In this point of view, cutting process model is described as a function whose input is feed and output is cutting thrust or cutting torque. In general, the relation between feed f (mm/rev) and cutting force F (N) or cutting torque T (Nm) are given as the following relations[6]:

$$F=\alpha_F \cdot K_s \cdot D \cdot g_F(f) \cdot (1+J_F(Z)) \tag{1}$$

$$T=\alpha_T \cdot K_s \cdot D^2 \cdot g_T(f) \cdot (1+J_T(Z)) \tag{2}$$

where α_F and α_T are constants depending on the tool shape, K_s is a specific cutting force(N/mm^2) depending on the hardness of the workpiece and D is a drill diameter(mm). The tool wear, which increases α_F and α_T, is ignored here. The function $g_F(f)$, $g_T(f)$ define the basic relation between f and F, f and T respectively. $g_F(f)$, $g_T(f)$ depend on the cutting tool and not affected by the work piece. $g_F(f)$ and $g_T(f)$ are given as empirical relations :

$$g_F(f)=f^{dF}+b_F \tag{3}$$

$$g_T(f)=f^{dT}+b_T \tag{4}$$

We call exponents d_F,d_T and constants b_F,b_T load coefficients in this paper. Load coefficients depend on the tool shape.

The function $J_F(Z)$,$J_T(Z)$ represent the increase ratio of F,T caused by the chip jamming, where Z is a Z-axis position from the surface of the workpiece. The theoretical modeling of the chip jamming is difficult because it is a stochastic phenomenon. According to the experimental results, $J_T(Z)$ are given approximately as:

$$J_T(Z)=\begin{cases} 0 & : Z \geqq L_{Tj} \\ c_T\left((Z-L_{Tj})/D\right)^m & : Z < L_{Tj} \end{cases} \tag{5}$$

$$L_{Tj}=r_T \cdot D \tag{6}$$

$$r_T=\begin{cases} r_{TI} : \text{when initial cutting} \\ r_{TR} : \text{when retry cutting} \end{cases} \tag{7}$$

where L_{TI} is a Z-axis position when chip jamming happens and it is proportional to D. Typical value of r_{TI} is from 3 to 5, and m is 2. But when using the pecking cycle, the value of r_T decreases when retrying the cutting after a chip jamming occurred. According to the experiment, typical value of r_{TR} is from 0 to 1. Similar relation is found concerning the thrust force, although the sensitivity of F to chip jamming is smaller than that of T.

In this paper, the cutting process optimization under different workpieces with various hardness and variation of the chip jamming is discussed. The variation of the hardness of the workpiece corresponds to the variation of K_s, which varies randomly according to the workpiece. The variation of the chip jamming can be modeled as the variation of c_T, r_{TI}, r_{TR} which have the normal distributions. Cutting tool change or tool wear is not considered here. When the cutting tool is fixed, $\alpha_F \cdot K_s \cdot D$ in Eq.(1) and $\alpha_T \cdot K_s \cdot D^2$ in Eq.(2) are constants, which we named K_F, K_T individually. K_F, K_T correspond to the machinability of a workpiece, so we call them machinability coefficients in this paper. Using K_F and K_T, Eq.(1) and (2) are simplified as follows:

$$F=K_F \cdot g_F(f) \cdot (1+J_F(Z)) \tag{8}$$

$$T=K_T \cdot g_T(f) \cdot (1+J_T(Z)) \tag{9}$$

To Sum up, when the cutting tool is fixed, K_F, K_T vary randomly dependant on the workpiece, $g_F(f)$,$g_T(f)$ are constant, and $J_F(Z)$, $J_T(Z)$ vary randomly in every hole even in the same workpiece .

K_F, K_T can be identified using the monitored F,T obtained while cutting the initial several holes in each workpiece. $g_F(f)$, $g_T(f)$ may be given, or even if they are unknown, can be identified using the monitored F,T obtained while cutting the initial several holes in each workpiece. In contrast, $J_F(Z)$, $J_T(Z)$ can be identified statistically through many experiments.

THE CUTTING CONDITION DETERMINATION

At the machining of passenger's cars important parts, such as cylinder blocks, cylinder heads and transmission cases, several shallow holes are often machined successively. Such workpieces are usually made of cast iron, so the large variation of the hardness is often existing, which causes the difficulty finding the adequate cutting condition like feed. Instead, chip jamming seldom occurs in such shallow holes, so this factor can be neglected.

In such cases, realtime adaptive feed rate control technique with cutting thrust and/or cutting torque constraints is often applied[3]. But even though this technique is applied, the question how to determine the adequate initial cutting condition is still unsolved. Selecting the adequate initial cutting condition affects the productivity much especially in high speed machining, because cutting time in each hole is so short that adaptive controller does not have the enough time to increase feed in a hole. The proposed method to determine the initial cutting condition is shown below.

Data flow

Fig.3 shows how to determine the adequate cutting condition when drilling a series of hole. Only a method to use F is shown because of the limited space here.

First, before cutting, in step 1, initial cutting condition is set to f_0 stored in the database. This value is a standard value with which F will

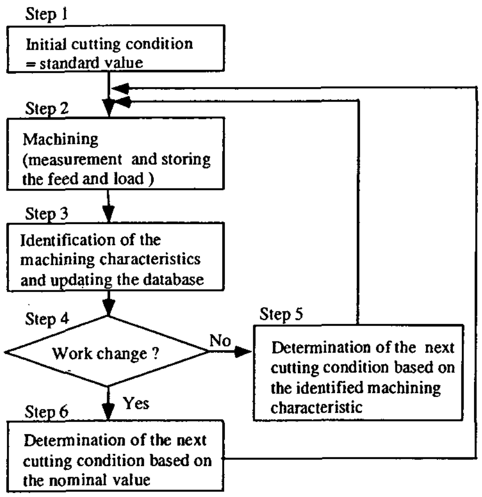


Fig.3 Data flow for the cutting condition determination

not go over than the threshold in most cases considering the variation of the hardness of the workpiece. f_0 are often provided by the cutting tool maker. It is clear that this feed f_0 gives the very low productivity.

Next, in step 2, during machining with the cutting condition set in step 1, f, F and T are measured and stored in the memory. After cutting, cutting characteristics like K_s, $g_F(f)$, $g_T(f)$ are identified using the stored data in step 2.

After cutting, in step 3, machinability coefficients are identified from the f ,F and T. Load coefficients, if they are unknown, are also identified similarly. Moreover, standard machinability coefficients(κ_F) are calculated statistically from the past machinability coefficients. For example, κ_F is calculated from the average value of the last several machinability coefficients. These identified parameters are stored in the database.

If the machinability coefficient is unknown and the load coefficients are known, at least one set of feed f and cutting thrust F at any time t yields the least square method's solution. For example, at the second hole, machinability coefficient will already be estimated from the measured data at the previous hole as long as the tool is not changed.

If both the machinability coefficient and load coefficients are known, at least n+1 sets of feed f_i and cutting thrust F_i at time t_i (i=1,2,...,n+1) yield the least square method's solution. Here, n is a number of load coefficients. These data are sampled at several holes with constant feed in each hole or at a hole with real time adaptive control of feed rate.

Then, if tool is not changed, next cutting condition is determined from the machinability coefficients and load coefficients of the current workpiece, in step 5. Here, past measured data of the current workpiece are available, so the cutting condition for the next hole is determined by the characteristic of the current workpiece. As shown in Fig.4, if function $g_F(f)$ is known, adequate feed is determined directly from the result machined at the same workpiece. That is to say, feed for the next hole f_{next} is determined as:

$$f_{next} = g_F^{-1} (F_{opt} / K_F) \tag{14}$$

where F_{opt} is a optimal cutting force, andK_F is an identified value in stpe3. In contrast, if the function $g_F(f)$ is unknown, f may be determined assuming that f is linear to the F roughly

$$f_{next}' = f_{prev} F_{opt} / F_{prev} \tag{15}$$

where f_{prev} is a feed of the previous hole, and F_{prev} is a cutting thrust of the previous hole. Eq.(14) reduces the iteration of the searching the optimal feed compared to the Eq.(15), which means the improvement of the productivity at initial several holes when the f has not reaches the optimal state.

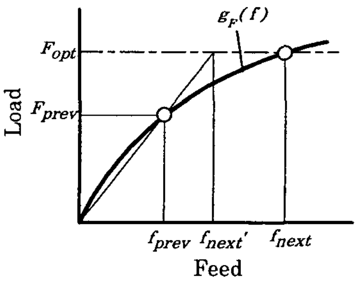


Fig.4 The relation between feed and the cutting force (mathematical model)

On the contrast, if tool is changed, cutting condition is determined from the standard machinability coefficients and load coefficients stored in the database in step 6. Here standard machinability coefficient (κ_F) is used to determine the optimal cutting condition:

$$f_{opt} = g_F^{-1} (F_{opt} / \kappa_F) \tag{17}$$

It is clear that f_{opt} produces the high cutting thrust if the actual machinability coefficient is bigger than κ_F. So in order that cutting thrust gets lower than F_{opt} in most cases, it is desirable to used the following initial feed:

$$f_{ini} = g^{-1} (F_{opt} / (\kappa_F + n_s \sigma)) \tag{18}$$

where σ is a standard variation of the distribution of K_F, and n_s is a constant that tune the balance of productivity and reliability.

THE ADAPTIVE CONTROL METHOD DETERMINATION

Suppose the workpiece is made of steel and the depth of hole is deep. In this case, chip jamming happens occasionally, which causes the difficulty finding the adequate cutting condition. The variation of the hardness of the steel is smaller compared to the cast iron, so this factor is assumed to be negligible here.

In such a case, pecking cycle has been used widely. Authors have proposed the adaptive pecking technique [7] which judges the pecking timing from the monitored cutting thrust and/or cutting torque. Or adaptive control technique with cutting thrust and/or cutting torque constraints may be still effective in a somewhat deep hole.

These techniques may fulfil the objective, but performances (e.g.cutting time) are different. So this study proposes the method to determine the optimal adaptive control method among available candidates. Of course, the question how to determine the adequate initial cutting condition or adaptive control parameters line threshold should be solved at the same time. The concept of the proposed method can be applied to any candidate of adaptive control method.

SIMULATION MODEL

It is desirable to determine an optimal adaptive control method before cutting, because dynamic switching of the adaptive control method during cutting has a risk of the transient instability of the machining state which often causes the deterioration of the productivity, reliability and quality.

In order to find an optimal adaptive control method before cutting, constraints and performance evaluation is executed by simulation using the cutting process model, motion control model and adaptive control model. In order to give a practical answer, the following factor should be included in the models. The cutting process model should consider the statistical variation of the process parameters. The motion control model should consider at least acceleration/deceleration, servo control. The adaptive control model should consider the adaptive control time response.

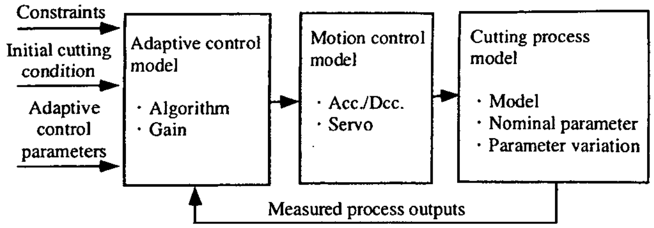


Fig.5 Simulation model for adaptive control method determination

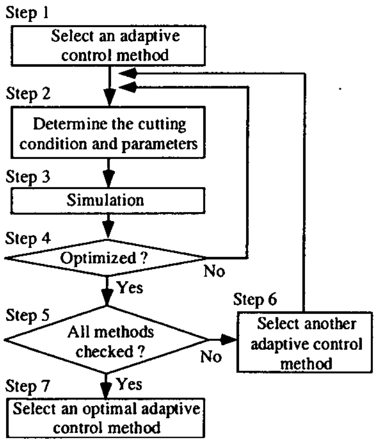
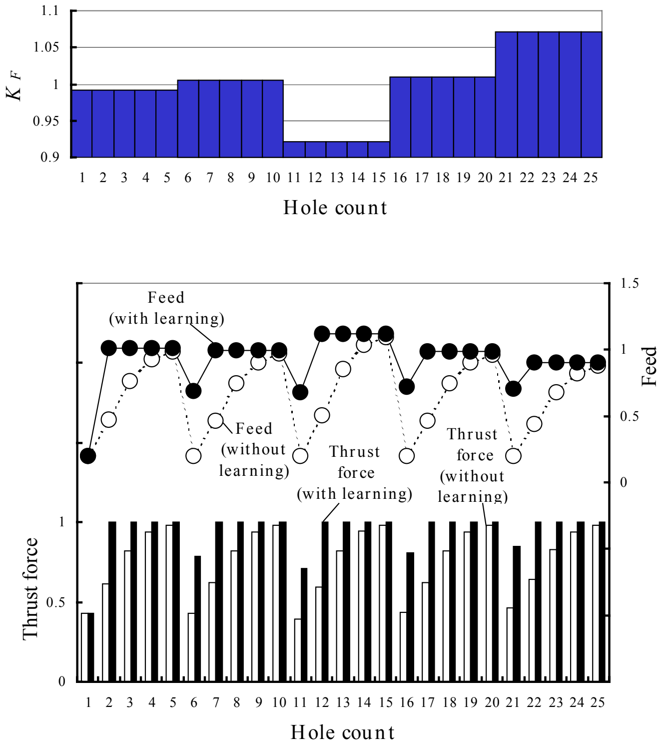


Fig.6 Data flow for the adaptive control method selection



(b) The change of feed and cutting force

Fig.7 The change of K_F, feed and cutting force controlled by the proposed method
(Simulation result :$K_F=1$,$b_F=0.2$,$F_{opt}=0.7$,$f_0=0.1$)
(●:with learning,○:without learning)

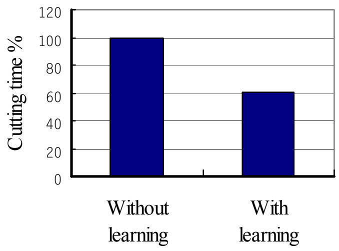


Fig.8 Cutting time reduction by learning
(Simulation result :$K_F=1$,$b_F=0.2$,$F_{opt}=0.7$,$f_0=0.1$)

Data Flow

Fig.6 shows how to determine the adequate control method.

First, in step 1, a voluntary adaptive control method is selected.

Next, in step 2, the cutting condition and parameters are determined. They are calculated from the given drilling specifications (e.g. K_F, F_{opt} and cutting speed) and previous simulated results, if available. Then, in step 3, adaptive control behavior is simulated and F and/or T are estimated. The procedures in steps 2, 3 and 4 are repeated until optimized enough. Some of the parameters may determine without any simulation, and other parameters may need several repetitions of the simulation and the determination. The number of repetitions depends on the adaptive control methods and the required accuracy of the optimization.

If the cutting conditions and parameters are fully optimized, another adaptive control method is selected in step 6 and same optimization procedures (steps 2-4) are executed. When all methods are checked, then finally, cutting time for each adaptive control method is compared in step 7, and an adaptive control method that gives an shortest cutting time is selected as an optimal adaptive control method.

Thus, an optimal adaptive control method can be determined.

SIMULATIONS AND DISCUSSIONS

Simulations were conducted to validate the proposed algorithm.

Case Study 1: Shallow hole drilling for cast iron

In this case, cast iron is used as workpiece.K_F is assumed to follow the normal distribution of $N(1,0.15^2)$ according to the variation of the hardness of the workpiece. The hardness of each workpiece is supposed to be unknown before cutting. The depth of the hole is assumed to be shallow enough that the chip jamming never occurs.

Each workpiece is drilled 5 holes, and 5 workpieces are machined, that is, totally 25 holes are drilled. The candidate of adaptive control method here is only an inter-process adaptive control of feed rate with cutting thrust constraint. The real time adaptive control of feed rate is not so effective because the time response of it is long compared to the cutting time in a high speed machining of a shallow hole. It is clear that the adaptive pecking has no effect. So an adaptive control method is fixed here, and the problem is simplified to how to find the appropriate cutting condition under the varying harness of the workpiece. The relation between feed and cutting thrust is given as Eq.(3) ,where $b_F=0.2$, $d_F=1$.

The proposed method and conventional method defined below are compared:

Proposed method (with learning)
Initial feed after workpiece change: $f_0=0.1$ as a save value
Next feed in a same workpiece: follows Eq. (15)

Conventional method (without learning)
Initial feed after workpiece change: follows Eq. (18)
Next feed in a same workpiece: follows Eq. (14)

Simulation results are shown in Fig.7. In this figure, the subfigure(a) shows K_F, and the subfigure (b) shows feed and thrust force. Horizontal axes of both subfigures are hole count. As seen from the subfigure (a), K_F is assumed to vary for each workpiece and is constant in the same workpiece. White bars in the subfigure (b) show F without learning, and black bars with learning. Both bars are normalized by the F_{opt}. Dotted line with white circles shows the feed without learning, and straight line with black circles shows the feed with learning. Both feeds are normalized by the f_{opt}. As seen from the feed and cutting thrust, when without learning, it takes much time to reach at F_{opt} because the initial feed is low and F do not reach F_{opt} in one iteration. In contrast, when with learning, feeds are higher than those without learning, because adequate initial feed are calculated at the second workpiece or later, and F reaches F_{opt} in only one iteration.

Fig.8 shows the total cutting time of 25 holes with or without learning. Cutting time is normalized by the cutting time without learning. Cutting time of each hole is inversely proportional to the feed of each hole. As shown in Fig.6, the cutting time was reduced by about 40% in this case. Note that only the cutting time is counted here and positioning, retraction or time to accelerate or decelerate is not considered.

Case study 2) Deep hole drilling for steel

As stated earlier, chip jamming happens occasionally in this case and the variation of the hardness of the steel is negligible here.

In such a case, several adaptive control methods (including a non adaptive control method) may be applicable.

(a)Fixed pecking(FP): Conventional pecking cycle is used. No adaptive control is applied. Pecking pattern do not change while cutting.

(b)Adaptive pecking(AP): This method judges the pecking timing from the monitored cutting torque go over the given level(T_{ap}).

(c)Real time adaptive control of feed rate(AFC): This method controls the feed in real time with cutting torque constrain ts.

All methods should satisfy the cutting torque constraint, which threshold is T_{th}. In all cases, initial feed is selected as $(1\text{-}C_s)\cdot T_{th}/K_F$ where C_s is safety coefficient (0.3 is used in the simulations). The parameters for each method are also chosen to satisfy the constraint. For example, the method FP has two parameters: first pecking point Z_p and pecking step in each cutting Q. Z_p is determined from the result of the first simulation (Z_p=Q=∞) and the pecking step in each cutting Q are determined from the result of the second simulation(Z_p is a calculated above, Q=∞).The parameter determination for the method AP is simple: just set T_{ap} = T_{th} .For the method AFC, it is rather complicated. The method FP has two parameters: adaptive control gain(G_{afc}) and cutting torque reference (T_{afc}). G_{afc} should be smaller than the inverse of the total response time of cutting process, motion control and adaptive control in order to stabilize the adaptive control system. Note that the cutting process gain (F/f) varies quite much when the chip jamming occurs which obstructs raising G_{afc}. Of course, this limitation depends on the controller type: a simple I control is used in the simulation.

The other parameters used at the simulations are follows:

Acceleration(A)=0.1～1G, 'S' shape acc./dcc. time constant=60ms
Rapid traverse rate=60m/min,Servo response time constant=20ms
D = 8.5mm, Depth of hole $\underline{L}$ = 2.5D～5.5D, R point=5mm
Cutting speed=100m/min, K_T = 2.5 (Nm/mm)
c_T =2 (1+$j_{var}\cdot v$), r_{TT}= 3.5(1+$j_{var}\cdot v$), r_{TR}= 0.2(1+$j_{var}\cdot v$)
j_{var} indicates the magnitude of variation.
v varies on the normal distribution N(0,1)

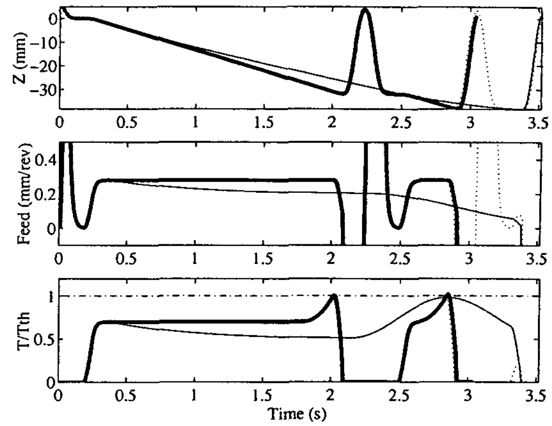


Fig.9 Time chart of Z,feed and T/T_{th} (simulation) (L/D=4.5,A=1G,j_{var}=0.2)

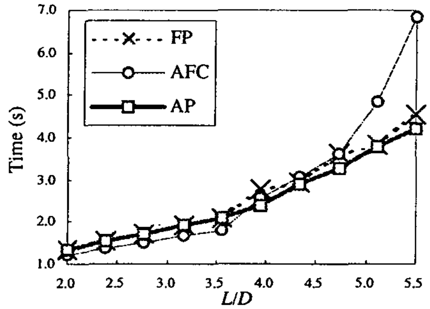


Fig.10 The relation of L/D and the cutting time (simulation) (A=1G,j_{var}=0.2)

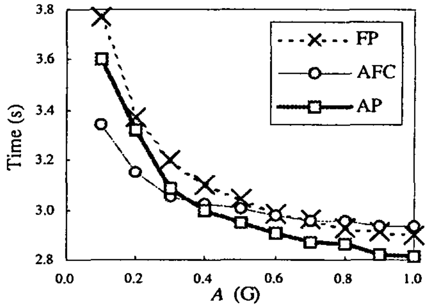


Fig.11 The relation of A and the cutting time (simulation) (L/D=4.2,j_{var}=0.2)

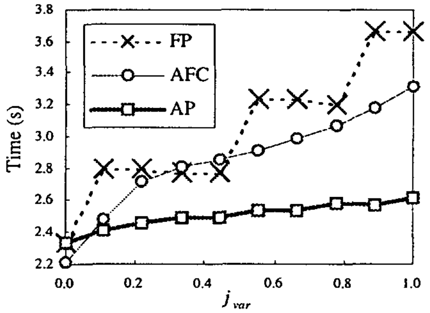


Fig.12 The relation of j_{var} and the cutting time (simulation) (A=1.0G,L/D=4)

Fig.9 shows the time chart of Z(upper subfigure),feed(middle subfigure) and T/T_{th} (lower subfigure)in each control method. In each subfigure, dotted line shows FP, thin line shows AFC and thick line shows AP. It this case, AP gives the shortest cutting time.

Using the simulated results like shown Fig.9, the relation of the L/D, A or j_{var} to the cutting time are examined.

Fig.10 shows the relation of L/D and the cutting time in each control method. In Figs.10,11 and 12, dotted line with mark X shows FP, thin line with mark ○ shows AFC and thick line with mark □ shows AP. It is seen that the cutting time gets longer as L/D increases in every control method, AFC is suited for a shallow hole and AP is suited for deep hole.

Fig.11 shows the relation of A and the cutting time in each control method. It is seen that the cutting time gets shorter as A decreases in every control method, AFC is suited if A is small and AP is suited if A is big.

Fig.12 shows the relation of j_{var} and the cutting time in each control method. It is seen that the cutting time gets shorter as j_{var} increases in every control method, AP is suited if j_{var} is big. The cutting time of AP and FP coincide each other when j_{var} is 0. Stepwise shape of the line of FP corresponds to the number of pecking.

Using the simulated data corresponding to L/D=2.5～5.5 and j_{var}=0～1, the cutting time in each control mode are examined(Fig.13). It is observed that as the j_{var} or L/D increases cutting time of FP or AFC increases drastically. In contrast, the cutting time of AP is affected by j_{var} only a little.

Using the results shown in Fig.13, optimal control method can be decided. Fig.14 shows the optimal control method corresponding to each L/D and j_{var}. The white areas show that FP give shortest time (actually same as AP), the light area show that AFC give shortest time and the dark area show that AP give shortest time.

In order to evaluate the effect of using the optimal control mode, the average of the cutting time ratio in each area in Fig.14 is calculated. It is seen that optimal control mode gives the shortest cutting time compared to using the fixed control mode. The reduced time ratio is from 5% (compared to AP) to 20 % (compared to AFC).

CONCLUSIONS

The conclusions obtained in this study are as follows:

1) The algorithm is proposed which determines the adequate initial cutting condition for the workpiece with a supposed-to-be unknown hardness. This algorithm consists of the identification the cutting characteristic, cutting condition determined based on the cutting characteristic and then standard characteristic in database update.
2) The algorithm is proposed which determines the optimal adaptive control mode among available candidates. This algorithm selects the optimal control mode comparing the cutting time for each control mode estimated by the simulation. The simulated results can be arranged to the optimal control method's map which is suited in industrial use.
3) Simulations were conducted to validate the algorithm presented. A case study of the shallow hole drilling of the cast iron showed that the proposed method reduces the cutting time by about 40%. Another case study of the deep hole drilling of the steel showed that the proposed method reduces the cutting time by about 5-20%.

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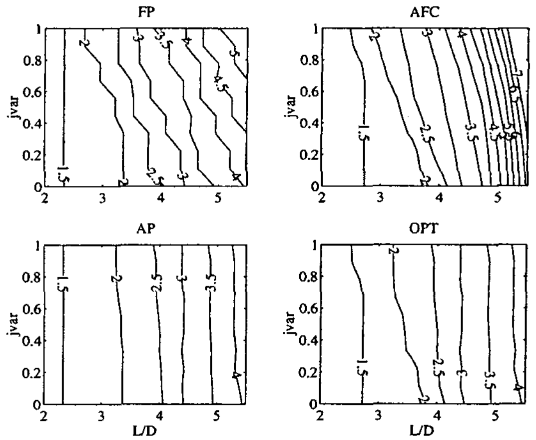

Fig.13 The cutting time in each control mode(simulation)
(A = 1.0 G)

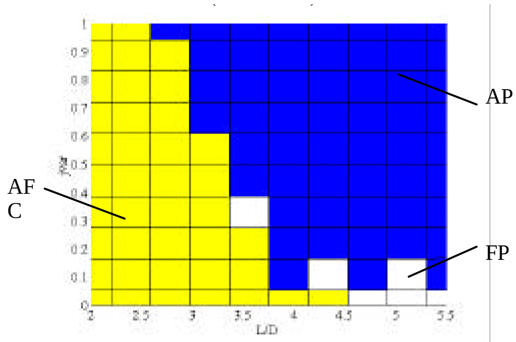

Fig.14 Optimal control method map (simulation)
(A = 1.0 G)

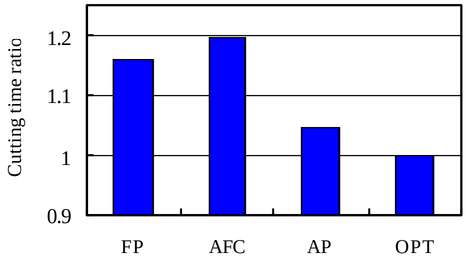

Fig.15 Cutting time ratio comparison (simulation)
(A = 1.0 G)

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