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NETWORKED FUZZY CONTROL SYSTEM FOR A HIGH-PERFORMANCE DRILLING PROCESS

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ABSTRACT

In order to improve drilling efficiency while preserving tool life, the current study focuses on the design and implementation of a simple, optimal fuzzy-control system for drilling force. The main topic of this study is the design and implementation of a networked fuzzy controller. The control system consists of a two-input (force error and change of error), single-output (feed-rate increment) fuzzy controller.

The control algorithm is connected to the process through a multipoint interface (MPI) bus. The output (i.e., feed-rate) signal is transmitted through the MPI; therefore, network-induced delay is unavoidable. The optimal tuning of the fuzzy controller using a maximum known delay is based on the integral time absolute error (ITAE) criterion.

The main advantage of the approach presented herein is the design of a simple fuzzy controller using a known maximum allowable delay to deal with uncertainties and nonlinearities in the drilling process and delays in the network-based application. The results demonstrate that the proposed control strategy provides an excellent transient response without overshoot and a slightly higher drilling time than the CNC working alone (uncontrolled). Therefore, the fuzzy-control system reduces the influence of the increase in cutting force and torque that occurs as the drill depth increases, thus eliminating the risk of rapid drill wear and catastrophic drill breakage.

INTRODUCTION

The high-performance drilling (HPD) process has a major impact on production technology in many industries, such as the automotive, die/mold and aerospace industries. However, up-to-date cutting conditions for drilling are generally chosen from the machining-data handbook, and an operator's sophisticated experience and skill are required. Therefore, the operator must adjust the cutting speed if the machining process is time-consuming or unstable, if there is drill overload or if there are machine-tool vibrations.

As the drilling depth increases, chips cannot be discharged smoothly from the hole, and friction thus rises between drill and workpiece. Higher cutting forces and drilling torques also have negative effects, such as rapid drill wear, tool vibration and the risk of catastrophic tool breakage [1]. HPD operations when the depth of the hole is less than the diameter of the drill are not very troublesome in terms of the influence of chips and temperature [2]. If the drilling depth is more than three times the drill diameter, peck drilling is recommended, to enhance chip removal and tool cooling. This drilling strategy as well as others based on similar principles cannot prevent the increase in the cutting force and torque as the depth of cut increases, nor can they avert the risk of rapid drill wear and catastrophic drill failure.

One way to compensate for the influence of drilling depth on useful tool life while enhancing productivity is to introduce real-time control of the cutting force [3]. The design and implementation of a real-time force-control system within the framework of the current trend toward network-based applications (e.g., distribution of optimizing functions and resources of machine tools) pose further technical difficulties related with unavoidable network delay, as well as many advantages, such as flexibility, maintenance time and cost.

Artificial-intelligence-based control techniques have raised considerable interest in the scientific community as regards the design of NCSs. Aoki et al. [4] proposed a control system with the parallel coupling of a fuzzy lag compensator with a fuzzy PI controller to regulate a dead-time process. Zhang and Jing [5] addressed the combination of fuzzy logic and an LQR controller to avoid the difficulty of an LQR implementation. Almutari and Chow [6] suggested the introduction of PI gain adaptation by fuzzy logic to compensate for the delays in an NCS application. The main advantage is that they do not require plant models and measurement of network delay for control-system design. Nevertheless, other techniques that have been successfully applied to optimize high-performance drilling processes, such as neural-network and evolutionary-algorithm-based strategies, have the main disadvantage of computation time (e.g., on-line learning algorithms), which limits the performance of intelligent control systems in network-based applications.

However, the majority of the work in machining optimization is devoted to the issue of adaptive techniques [7]. Adaptive controllers are extremely time intensive, since parameters are estimated online and controller gains are adjusted accordingly. Furthermore, adaptive-control systems must be carefully tuned, and sometimes they exhibit complex and undesirable behavior.

In order to improve drilling efficiency while preserving useful tool life, this study focuses on the design and implementation of a fuzzy-control system for drilling force. The main topic of this study is the design and implementation of a networked fuzzy controller using a fieldbus. The control algorithm is connected to the process through a multipoint interface (MPI) bus, a proprietary programming and communication interface for peer-to-peer networking that resembles the PROFIBUS protocol. As the output (i.e., feed-rate) signal is transmitted through the MPI, network-induced delay is unavoidable.

Fuzzy logic was selected out of all of the available techniques because it has been proven to be useful as a highly practical optimization tool for control in industrial settings [8]. The main advantage of the approach described herein is the design of a simple fuzzy controller on the basis of a known maximum allowable delay bound to deal with uncertainties and nonlinearities in the drilling process and delays in the network-based application. The optimal tuning of the fuzzy controller is based on an ITAE performance index in order to obtain a short rise time and free-overshoot time response.

This paper is organized as follows: Section II presents a brief study of the complex process of high-performance drilling; Section III describes the design of a fuzzy controller to optimize HPD; Section IV addresses the implementation of this fuzzy controller and its connection to the CNC machine tool through a Fieldbus; Section V shows the experimental results; finally, Section VI contains the conclusions.

2 DYNAMIC MODEL OF DRILLING FORCE

The modeling of an HPD process includes the modeling of the feed-drive system, the spindle system and the cutting process. In this study, the plant model is obtained by experimental identification using different step-shaped disturbances in the command feed. The drilling force, *F*, is proportional to the machining feed. The cutting-process gain and its magnitude vary depending on the workpiece and the drill diameter.

An earlier mathematical model of the drilling force for steel and aluminum [3] considered the relationship between drilling force and feed rate as a first-order system represented as follows:

$$G_P(s) = \frac{F(s)}{f(s)} = \frac{K}{\tau s + 1} \tag{1}$$

where K is the static gain related to the cutting stiffness and τ is the time constant.

In this study, the whole system of the feed drive, cutting process and dynamometric platform is modeled as a third-order system, and the transfer function can be represented as follows:

$$G_P(s) = \frac{F(s)}{f(s)} = \frac{1958}{s^3 + 17.89 \cdot s^2 + 103.3 \cdot s + 190.8} \tag{2}$$

where s is the Laplace operator, f is the command feed and F is the cutting force.

In fact, model (2) above has certain limits in representing the complexity and uncertainty of the drilling process. However, it does provide a rough description of the process's behavior, which is useful for the optimal tuning of a network-based control system.

3 NETWORK-BASED FUZZY-CONTROL SYSTEM FOR CUTTING FORCE

Often, to avoid rapid tool wear or catastrophic tool breakage, conservative constant drilling parameters are set by hand feeding on the basis of the operator's experience. The feed rate can be adjusted to regulate the cutting force, and the production rate can be optimized without concern for drill damage due to over-force/torque acting on the tool. The fuzzy controller can respond to the increase in friction between the drill and workpiece and work-material hardness by adjusting this variable.

The standard steps for defining input and output membership functions and for constructing fuzzy-control rules were followed in designing a two-input/single-output fuzzy-control system. The fuzzy controller's core performs online actions to modify the feed rate. The manipulated (action) variable is the feed-rate increment (Δf as a percentage of the initial value programmed into the CNC). The error and output vectors are:

$$\mathrm{e} = \begin{bmatrix} K_e \cdot \Delta F & K_{ce} \cdot \Delta^2 F \end{bmatrix};\ u = GC \cdot \Delta f \tag{3}$$

where ΔF is the cutting-force error (in newtons), $\Delta^2 F$ is the change in cutting-force error (in newtons) and K_e, K_{ce} and GC are scaling factors for the inputs (error and change in error) and the output (change in the feed rate), respectively.

The reference force value (F_r) is derived from the tool/workpiece-material combination. For each sampling period k, cutting-force error and the change in cutting-force error are calculated as:

$$\Delta F(k) = F_r - F(k) \tag{4}$$

$$\Delta^2 F(k) = \Delta F(k) - \Delta F(k-1) \tag{5}$$

where ΔF is the cutting-force error (N) and $\Delta^2 F$ is the change in the cutting-force error (N) in *k*-instants.

The fuzzy partition of universes of discourse is based on prior knowledge and experimental results. The universe of discourse of input variables consists of three triangular-shaped membership functions in the range $[-150,150]$. The universe of discourse of output variables consists of five trapezoid-shaped membership functions equally spaced and set according to the maximum modification of the nominal feed rate under nominal cutting conditions (about 10% for nominal feed rate). Figure 3 shows the resulting fuzzy partition. Three and five fuzzy sets are used for the inputs and the output. These were NB, negative big; NM, negative medium; ZE, zero; PM, positive medium; and PB, positive big.

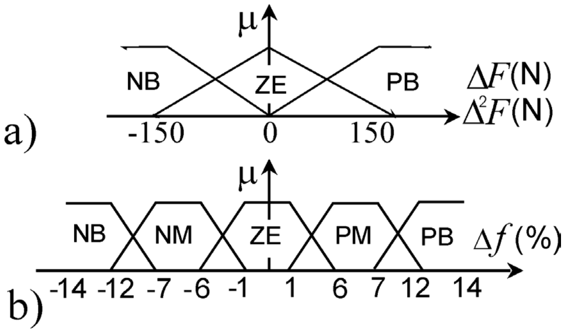


Fig. 1. a) Fuzzy partitions and membership functions for (a) ΔF, $\Delta^2 F$, (b) Δf

The membership-selection process is the result of combining the trial-and-error process with a number of empirical design guidelines established mostly from a knowledge-engineering standpoint and simulation studies [9]. Membership functions are essential for achieving good control performance. When trapezoidal membership functions are used, the resulting system is the sum of a global nonlinear controller (the static part) and a local nonlinear PI controller (which dynamically changes with regard to the input space) [10]. Therefore, this kind of membership function is relevant when dealing with nonlinear process behavior. The selection of the type of input and output fuzzy sets is a key step in fuzzy-controller design.

A set of rules are considered, consisting of linguistic statements linking each antecedent with its respective consequent, with the following syntax:

IF ΔF is PB AND $\Delta^2 F$ is PB THEN Δf is PB

These fuzzy rules provide important principles and relevant information about the process. Under normal cutting conditions, the constant feed rate is set conservatively according to information from data handbooks on machining, cutting tools and materials. However, the feed-rate values are manually adjusted in real time depending on the cutting parameters, in order to optimize the machining process. In order to maintain a constant cutting force, the feed rate should be reduced when the force increases (i.e., due to an increased depth of the cut). On the other hand, when the force decreases, the feed rate should be increased to maximize the rate of material removal. A total of 9 control rules is developed, as summarized in Table 1.

Table I. Rule base for manipulating feed rate

$\Rightarrow \Delta F$

$\Downarrow$ $\Delta^2 F$	N	Z	P
N	NB	NM	ZE
Z	NM	ZE	PM
P	ZE	PM	PB

The sup-product compositional operator is selected for the compositional rule of inference. Using the algebraic product operation, developing the fuzzy implication and applying the maximum union operation yields:

$$\mu_R(\Delta F, \Delta^2 F, \Delta f) = \max_{i=1}^{9} \left\{ \text{prod} \left\{ \mu_{\Delta F_i}(\Delta F), \mu_{\Delta^2 F_i}(\Delta^2 F), \mu_{\Delta f_i}(\Delta f) \right\} \right\}. \tag{6}$$

The crisp controller output, which changes the feed rate, is obtained by defuzzification using the center-of-average (COA) method, which is expressed as:

$$\Delta f = \frac{\sum_i \mu_R(\Delta f_i) \cdot \Delta f_i}{\sum_i \mu_R(\Delta f_i)} \tag{7}$$

where Δf is the crisp value of Δf_i for a given crisp input $(\Delta F, \Delta^2 F)$.

There are basically three traditional defuzzification methods: the maximum, mean of maxima (MOM) and center of area (COA). It has long been demonstrated that the COA yields less mean square error than the MOM [11]. In all cases, the maximum yields worse results than the other methods despite its simplicity and shorter computation time. From the viewpoint of the dynamics of the control loop, the MOM yields a better transient response, whereas the COA performs better at steady state. Additionally, the MOM behaves as a multilevel relay, and the COA behaves as a proportional-integral (PI) controller [12]. Other strategies for defuzzification have more recently been developed under the same rationale; namely, the formal treatment of uncertainty in relationship with the validity of the possibilistic distribution of the output generated by the decision-making process of fuzzy systems (i.e., conversion of the possibilistic distribution of the output fuzzy set into a probabilistic distribution function) [13]. The COA strategy is selected as the defuzzification strategy due to its suitable performance at steady state and its use in experimental and industrial fuzzy controllers. A survey of defuzzification strategies is given in [14].

The crisp-control action (generated for each sampling instant) defines the final actions that are applied. The strategy used to compute f determines what type of fuzzy regulator is used. In this case, it is a PI fuzzy controller. The output-scaling factor (*GC*) multiplied by the crisp-control action (generated at each sampling instant) provides the final actions that will be applied to the CNC machine-tool cutting parameters.

$$f(k) = f(k-1) + GC \cdot \Delta f(k). \tag{8}$$

3.1 Network-based Fuzzy Control Using a Fieldbus

PROFIBUS is a widely used fieldbus that operates via a master-slave relationship among devices connected to the network. Each master is assigned a set of slaves which it regularly polls on a periodic basis. Access to the network is regulated by a token moving among the masters. Distributed control systems based on PROFIBUS are affected by jitter due to the retransmission of data with slaves and the asynchronous activities performed by the masters.

The multipoint interface (MPI) is a programming interface for the Siemens SIMATIC S7 series that resembles the PROFIBUS protocol [15]. The MPI's physical interface is identical to the PROFIBUS RS485 standard. The transmission speed can be increased up to 12MB with the use of an MPI. The control-system architecture for a machine tool on the basis of an MPI network is shown in Figure 2.

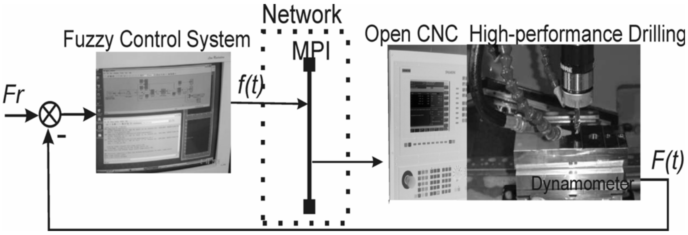


Fig. 2. Network-based fuzzy-control system architecture for a high-performance drilling process

As the control signal (command feed) is transmitted through the MPI, some amount of network-induced delay is unavoidable. Figure 3 shows the step response of the cutting force to the command feed in a high-performance drilling process. The maximum delay estimated from experiments is 0.4s, including both dead-time process and network-induced delay.

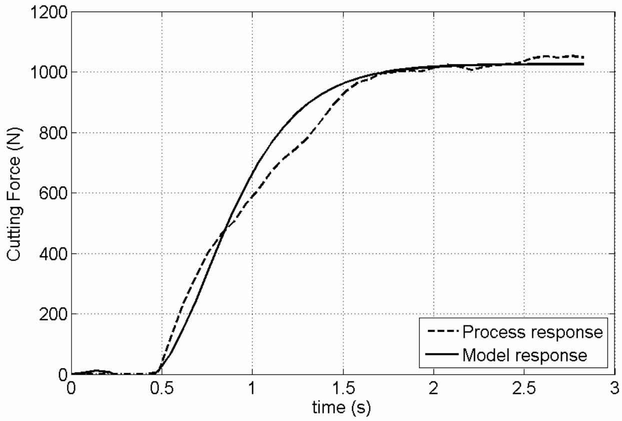


Fig. 3. Drilling-force response to command feed in high-performance drilling process using a network-based environment

4 IMPLEMENTATION OF THE FUZZY-CONTROL SYSTEM

This section briefly explains how the fuzzy controller (design shown in Section 3) that communicates with the open-architecture CNC through the MPI network is tuned and implemented.

The data-acquisition system consists of a dynamometer, a charge amplifier and hardware and software modules as depicted in Figure 4. The cutting forces are measured with a Kistler 9257B piezoelectric dynamometer mounted between the workpiece and the machining table. The electric charge is then transmitted to the Kistler 5070A four-channel charge amplifier through the connecting cable. The interface hardware module consists of a connecting block and an AT-MIO-16E-1 16-channel A/D acquisition card with a maximum sampling frequency of 500 kHz. The A/D device transforms the analogue signal into a digital signal so that the Simulink program is able to read data and the three axis force components can be obtained simultaneously, processed and displayed. Real-Time Windows Target (RTWT) allows for real-time execution of Simulink models [16].

The output of the fuzzy controller is connected to the process through a multipoint interface (MPI) with a default baud rate of 187.5 Kbits/s. A CP5611 card connects the PC that implements the fuzzy-control system to this network. The MPI messaging interface is a master client (active station) and manages exchanges with Siemens S7 PLCs. The system has two masters, the man-machine control (MMC 103) with a numerical-control kernel and a numerical-control unit (NCU 573.3).

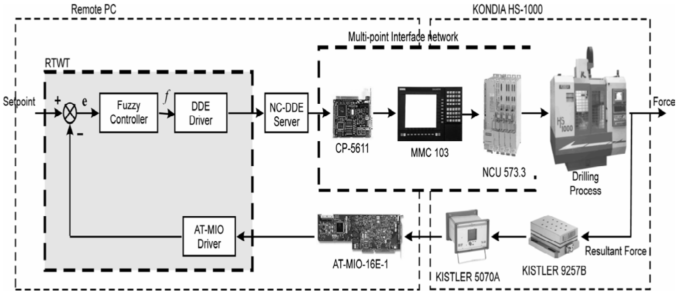


Fig. 4. Scheme of the experimental facilities and fuzzy-control system.

5 SIMULATION AND EXPERIMENTAL VALIDATION

In order to examine the performance of the closed-loop system, the fuzzy-control system is tested by simulation using Simulink. The scheme is depicted in Figure 5.

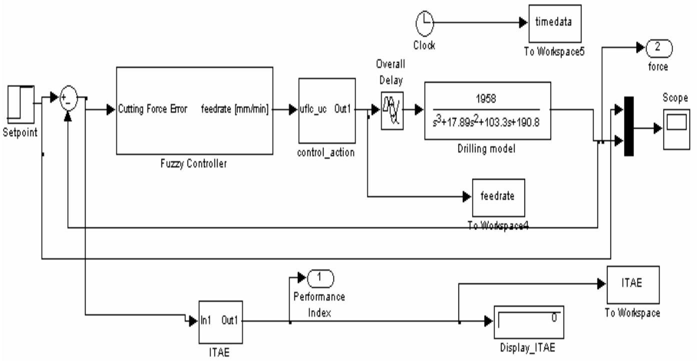


Fig. 5. Implementation of the fuzzy-control system in Simulink/Matlab.

In the optimization, the tuning of the fuzzy controller is based on an optimization criterion. The goal is to obtain the optimal tuning parameters for the input scaling factors $[K_e, K_{ce}]_{OPT}$ where the ITAE performance index has its minimum.

$$K_{OPT} = [K_e, K_{ce}]_{OPT} = \arg\min\left(\int_0^T \left|e(t)\right| \cdot t\,dt\right). \qquad (9)$$

The integral time square error (ITAE) performance index or cost function describes how well the system responds to an outside disturbance. In this study, a step in the force reference signal is considered a disturbance, and the goal is to assess how well the system follows set-point changes using ITAE criterion. The optimization is done here by using a simplex search algorithm for unconstrained optimization [17]. The cost function is evaluated through simulation, so a simulation model of the process is needed. The tuning is done with MATLAB/Simulink and the optimization toolbox. The minimum *ITAE*=463.07 is reached at iteration 64 and corresponds to $[K_e, K_{ce}]_{OPT} = [0.0559, 0.1156]$. The ITSE criterion is 3.0432x10^5, and the overshoot is 0.30%.

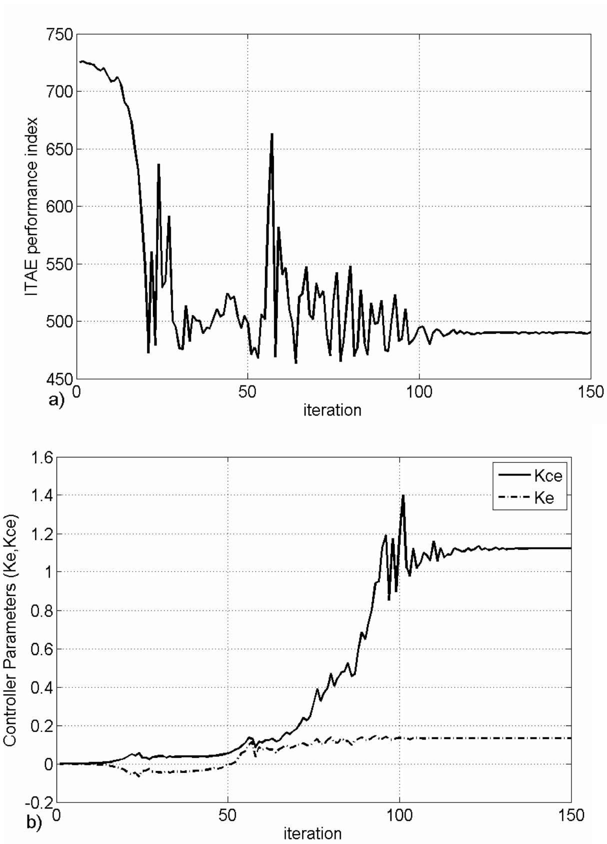


Fig. 6. a) ITAE performance index resulting from the optimization, b) the corresponding input scaling factors of the fuzzy controller.

The simulation results are depicted in Fig. 7. The system's step response is depicted in Fig. 7a. As shown in the figure, the cutting force is well regulated with respect to the reference value (dotted line).

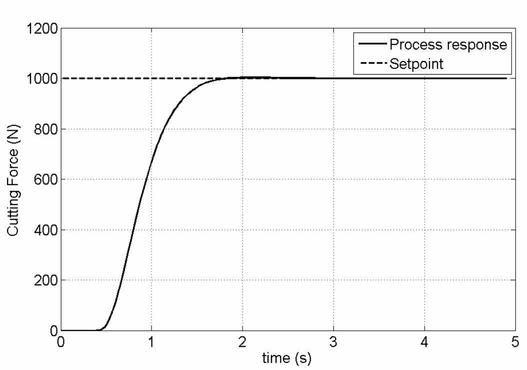


Fig. 7. a) Step response of the cutting force: simulation results

The time-varying delay L in the network-based application is simulated by assuming a random delay between 0 and 0.6s, and 100 simulation tests are run for each set of controller parameters. The maximum, minimum and mean value of the ITAE performance index and the overshoot are thus calculated. For the randomly generated minimum delay of 0.0077s, the overshoot was -0.86% and the ITAE performance index was 289.87. For the mean generated delay of 0.2783s, the overshoot was -0.2131% and the ITAE was 389.30. The worse case was for the maximum random delay, 0.5966s, where the overshoot was 1.38% and the ITAE was 697.30. Figure 8 shows the simulation results corresponding to the system's step response for all three delays. Figure 8a represents the cutting-force behavior, whereas Fig. 8b depicts the feed-rate variations in each case. It is inferred from the simulation results that the optimal tuning achieved in simulation guarantees an overshoot-free transient response with a rise time of about 0.7s.

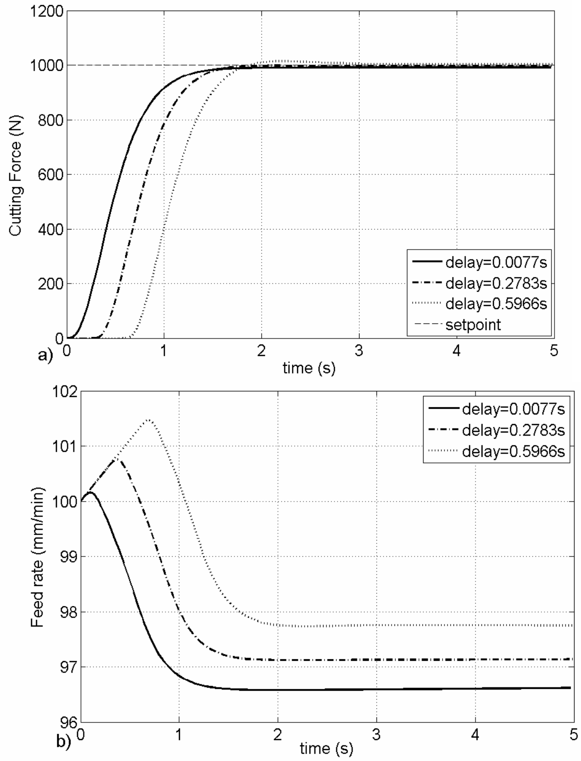


Fig. 8. a) Cutting-force behavior and b) feed-rate variations for the minimum, mean and maximum delay.

The influence of the delay on deteriorating performance indices is shown in Fig. 9. The increase of the ITAE and ITSE criteria as the delay increases is not very remarkable; the robustness of the fuzzy controller in the presence of dead time plus network-induced delay is thus corroborated. The ITAE (solid line) and ITSE (dashed line) performance indices increase nonlinearly with the delay.

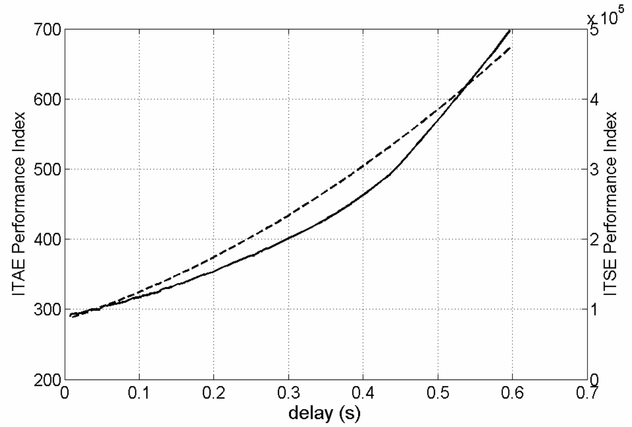


Fig. 9. Behavior of the ITAE (dashed line) and ITSE (solid line) performance indices in the presence of delays.

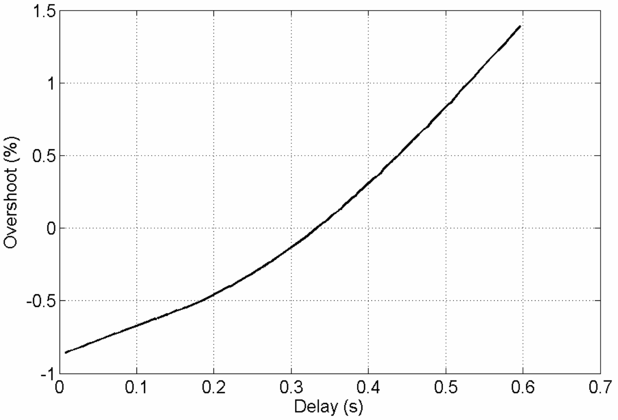


Fig. 10. Behavior of the overshoot in the presence of delays

The influence of the delay on the transient response is also analyzed considering random delay. The random delay is uniformly distributed between 0 and 0.6. Simulation analysis on the basis of 1000 delays samples is performed to assess the overshoot. Fig. 10 shows the behavior of the overshoot in the presence of delays up to 0.6s. A transient response with zero overshoot despite delays is evident from the overshoot pattern.

Experimental drilling tests are carried out on an HS1000 Kondia milling machine equipped with a Sinumerik 840D open-CNC controller. A 10-mm-diameter Sandvik cutting tool is used for the drilling operations. The workpiece material is GGG40 with a hardness number of 233 HB. Nodular cast iron is becoming popular for many engineering applications on account of its potential advantages (i.e., high strength and toughness, good fatigue and wear resistance). Due to the metallurgical nature of this material, the machining of nodular cast iron with conventional machining techniques such as milling and turning is problematic and difficult [18]. Controlled and uncontrolled drilling of standard GGG40 nodular cast iron is, then, a field ripe for investigation.

The nominal feed rate and nominal spindle speed are f_0 =100mm/min and s_0 =870rpm, with a maximum drill depth of 10 mm (the same as the drilling diameter). Photographs of the experimental setup are shown in Figs. 2 and 4.

Figure 11 shows the experimental results corresponding to drilling the GGG40 workpiece with a 10-mm-diameter drill. Figures 12a and 12b represent the controlled and uncontrolled force behavior and the feed-rate variations for both cases analyzed. In order to suppress the cutting-force increase, the feed rate is decreased gradually as the drilling depth increases, and the cutting force is quite well regulated at the given setpoint. The good transient response is endorsed by good performance indices for the ITAE (17.72), ITSE (9.23) and IAE (16.46). However, the drilling time is increased by 5.75% when the drilling force is controlled.

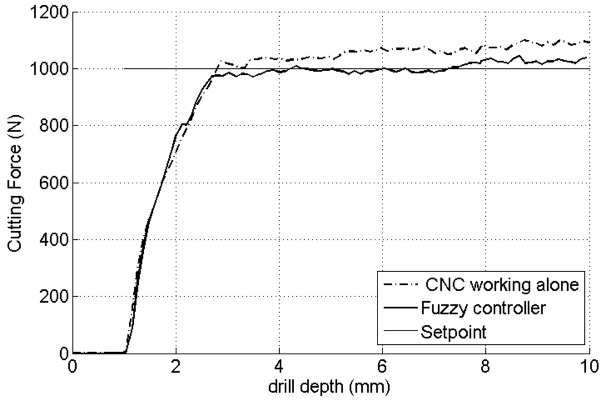
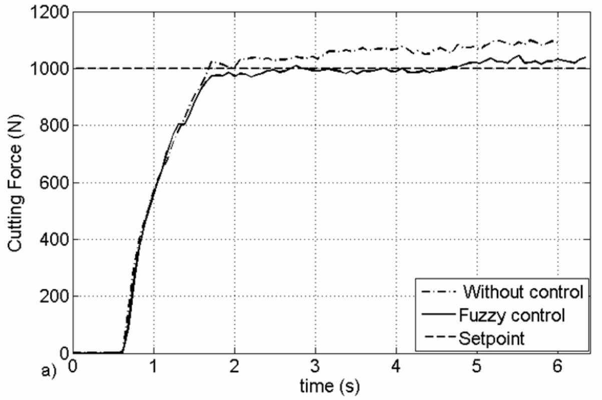


Fig. 11. Cutting-force behavior in relationship with drilling depth.

The experimental results corroborate that increases and fluctuations in force drilling can be suppressed despite an increase in drilling depth. Thus, the drilling process can be stabilized and the risk of drill failure can be greatly reduced through a fuzzy-control system.



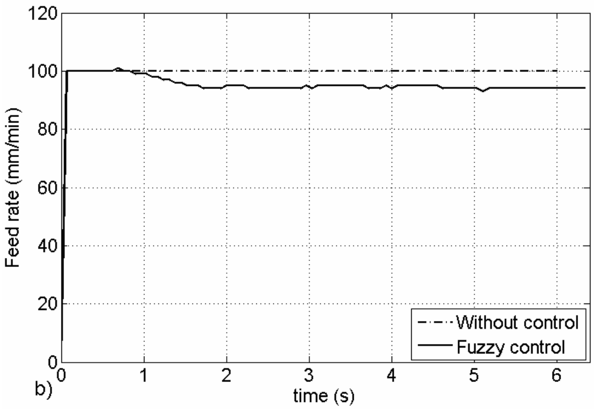


Fig. 12. Cutting-force and feed-rate variations in uncontrolled drilling and drilling controlled by a fuzzy regulator

CONCLUSIONS

This paper introduces a nine-rule, two-input/single-output fuzzy controller to regulate force for drilling-process optimization while maximizing useful tool life. The fuzzy-control system adjusts the feed as needed to regulate the drilling force using the CNC's own resources to modify the feed rate and a dynamometer to measure the drilling force.

The main advantage of the approach described herein is the design of a simple fuzzy controller using a known maximum allowable delay to deal with uncertainties and nonlinearities in the drilling process and delays in the network-based application. The results demonstrate that the proposed control strategy provides outstanding transient response without overshoot, small rise time, minimum steady-state error and slightly higher drilling time than the CNC working alone (uncontrolled drilling).

The proposed controller produces a non-oscillating system regardless of disturbances and nonlinearities, making it the correct choice for coping with drastic disturbances such as increase in drilling depth and variations in material properties.

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