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REGULAR PAPER

Development of process monitoring system in drilling process using fuzzy rules

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Abstract This study describes the development of process monitoring system in drilling process in high speed machining center. The system monitors the several state variables of the cutting process of a drill. However, the thrust force and torque signals have been chosen to detect and monitor the drilling process, the acoustic emission signal has been also analyzed. Experimental data have allowed defining statistical behavior of the variables for non-fault conditions, tool wear and breakage. The new approach in this project is to use the standard data acquisition software LabVIEW for the purpose of data collection, signal analysis, decision making and sending back the message to the machine.

Keywords Process monitoring · Drilling process · High speed machining center · LabVIEW · CNC

1 Introduction

Development of a methodology for process monitoring is now playing an important role in the manufacturing world. The increasing demands, such as quality control, cost reduction, are driving the performance of modern machine tools require the improvement of methods for process monitoring and control. Guaranteeing reliable production process and stable product quality is of central importance to industry (Smith 1993). This paper is one part of the development of process monitoring system in OpenCNC controller in high speed machining centre, focusing on the drilling process for several kinds of drills. Although numerous amount of process monitoring systems and many ideas have been presented in many research organizations and become available on the market, but none of them is not completely perfect for all ranges of the system. This paper describes a new inspiration of LabVIEW software for signal acquisition and feature extraction purpose in monitoring system. The sensor signals from the OpenCNC machine process are acquired via DAQ card and then feature extraction and decision-making steps are done in LabVIEW (Thyer 1988). The final monitoring system is integrated to OpenCNC machine via the signal output of DAQ card. One of the objectives of this paper is that it becomes a reference to any similar research work, doing with LabVIEW standard software.

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2 Proposed monitoring system

Many adaptive monitoring methods have been proposed with multiple constraints corresponding objective line tool wear, tool breakage or accuracy (Abele et al. 2002; Al-Habaibeh et al. 2002; Narayanan et al. 1994). But most of them are often effective only for the limited range of machining. This means that adequate adaptive methods, which suit each situation, should be selected, especially for the machine centres. The monitoring system should have to be open system for the unknown tool process. Here in this project, it monitors the drill tool condition by the analysis of the cutting force and cutting torque which acquired from the process simultaneously. The proposed open system is shown in Fig. 1.

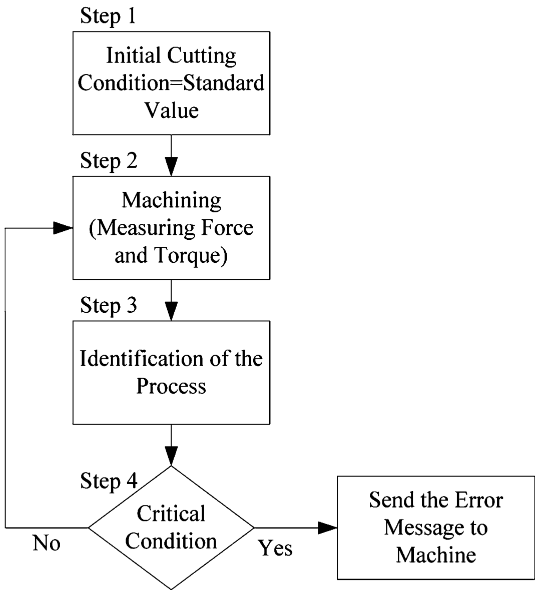

Fig. 1 Data flow for the cutting drill condition determination

This method measures the process signals (e.g. Thrust Force and Torque) during machine and identifies the process features (peak value, average value and standard deviation) from the measured process data. The identified process features are used to determine the initial cutting condition for the next operations. This initial condition is stored on the disk and is used to identify the next process. In addition to that, it is quite important to select an adequate adaptive monitoring method. In step 1, the initial drilling process signals (Thrust Force, Torque) are set to initial reference values. Peak level, Average value and standard deviations are calculated and saved as standard value. In step 2, during machining with cutting conditions set in the step 1, the process signals are measured and stored in the memory. At the same time the process characteristics are extracted. In the step 3, the process identification is evaluated decide whether the process is stable or not, means that whether the level of present signal is high or not. In step 4, the current status is checked and if it is the critical condition, the error message is sent to the machine immediately. By this way, the system works repeatedly until the process is critical condition or operator stops the monitoring system.

3 Strategy of tool breakage monitoring system

The main objective of this project is to set up the process monitoring system, to fulfil this objective, initially the signal processing strategy is needed to be developed. Fig. 2 describes the flow diagram of the signal analysis strategy for the tool breakage monitoring.

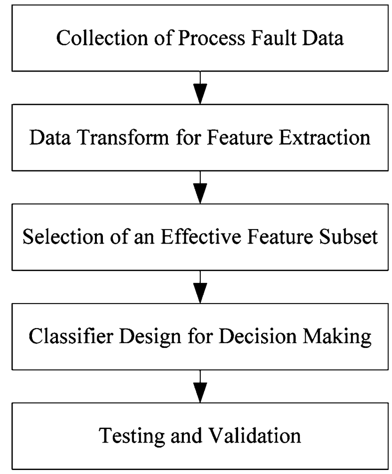

Fig. 2 Flow chart for tool breakage monitoring signal analysis

3.1 Collection of process fault data

At the beginning, the signals from tool breakage are analyzed (Liang et al. 2002). These signals are collected from the tool endurance test by using several strategies in the process. Determination of the peak value changes in the borehole cycles between the initial value and final value are calculated in Table 1. The second column in Table 1 represents the file name of measurement data. Several tool endurance tests have been carried out for the purpose of feature extraction in deep hole drilling. The abrupt changes of Torque and Force are analysed by comparing initial value and maximum value at tool breakage condition, see in Figs. 3, 4, 5 and 6 and Table 1 shows this analysis in detail.

3.2 Decision making part

Based on these facts which described above analysis, the decision making part can be built up as follows:

3.2.1 Input states

F	Current Force value from the process
T	Current Torque value from the process
F_R	Force Ratio between initial value and current value that is calculated from the process signal
T_R	Torque Ratio between initial value and current value that is calculated from the process signal

3.2.2 Output states

Critical condition	Stop the process after finishing the present working cycle and a pulse signal is sent to Digital Output Pin 1

Table 1 The analysis of force and torque signals in broken tools

No.	File name	Thrust force (N)			Torque (Nm)			Bore-hole
		Initial value	Maximum value	% Increment	Initial value	Maximum value	% Increment	
1	D07-b-03	84.039	111.520	133	0.0422	0.2675	634	4
2	D07-c-03	83.496	358.398	429	0.0416	0.2465	592	4
3	D11-c-02	87.470	190.660	218	0.0396	0.4997	1262	1
4	D08-a-03	79.345	244.870	308	0.0356	0.3980	1118	1
5	D12-c-01	58.590	179.440	306	0.0407	0.3718	914	1
6	D22-c-01	54.715	306.990	561	0.0317	0.3313	1045	1
7	D24-a-01	43.025	134.408	333	0.0232	0.3085	1330	3
8	P03-c-01	59.570	135.740	228	0.0466	0.2316	497	3
9	P03-c-02	93.990	166.303	177	0.0495	0.2060	416	3
10	P03-c-03	60.258	163.580	272	0.0425	0.2157	507	5
11	P04-a-02	107.43	265.136	247	0.0788	0.1767	224	1
12	P04-d-03	57.480	147.375	256	0.0290	0.1270	438	3
13	P04-e-02	99.480	273.260	275	0.0514	0.1799	350	6
14	P04-e-03	53.410	247.510	463	0.0283	0.1328	469	7
15	P04-d-05	75.540	224.120	297	0.0337	0.2065	612	3
16	P05-e-01	77.860	197.588	254	0.0374	0.1699	454	4
17	P07-b-02	85.090	215.570	253	0.0577	0.2890	501	1
18	P07-d-01	57.400	105.957	185	0.0246	0.1800	732	1
19	P08-d-01	56.410	96.670	171	0.0370	0.2778	751	1

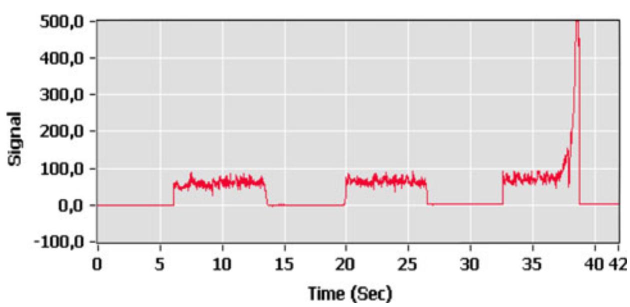

Fig. 3 Thrust Force signal from the file P03-c-01.dat

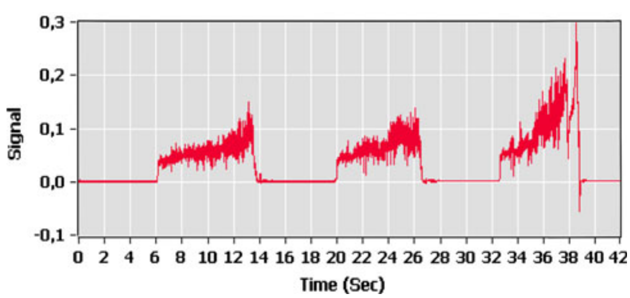

Fig. 4 Torque signal from the file P03-c-01.dat

Stop the process	Stop the Process immediately and a pulse signal is sent to Digital Output Pin 0

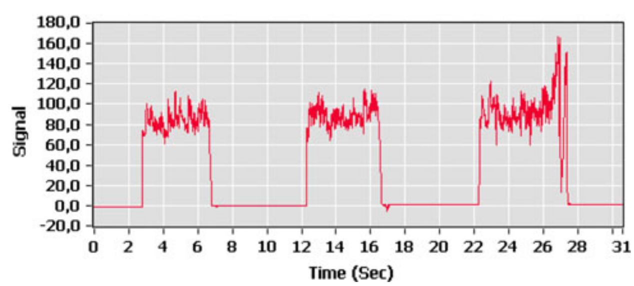

Fig. 5 Thrust Force signal from the file P03-c-02.dat

3.3 Operator define values or default values in rules

3.3.1 If, Then rules (The limits are defined for KHSS-E drill)

Rule 1: If F is greater than 200 N Then send the message "The tool is in Critical Condition, stop the process after the present working cycle" and Send the pulse signal to Digital output pin 0 of DAQ card.

Rule 2: If T is greater than 0.15 Nm Then send the message "The tool is in Critical Condition, stop the process after the present working cycle" and Send the pulse signal to Digital output pin 0 of DAQ card.

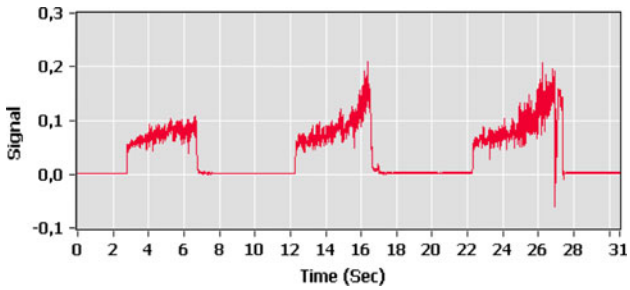

Fig. 6 Torque signal from the file P03-c-02.dat

Rule 3: If F_R is greater than 200% Then send the message "The tool is in Critical Condition, stop the process after the present working cycle" and Send the pulse signal to Digital output pin 0 of DAQ card.

Rule 4: If T_R is greater than 200% Then send the message "The tool is in Critical Condition, stop the process after the present working cycle" and Send the pulse signal to Digital output pin 0 of DAQ card.

Rule 5: If F is greater than 200 N and T is greater than 0.15 Nm Then send the message "Stop the process immediately." and Send the pulse signal to Digital output pin 0 of DAQ card.

Rule 6: If F is greater than 200 N and the force increment ratio is greater than 200% Then send the message "Stop the process immediately." and Send the pulse signal to Digital output pin 1 of DAQ card.

Rule 7: If F is greater than 200 N and torque increment ratio is greater than 200% Then send the message "Stop the process immediately." and Send the pulse signal to Digital output pin 1 of DAQ card.

Rule 8: If T is greater than 0.15 Nm and F_R is greater than 200% Then send the message "Stop the process immediately." and Send the pulse signal to Digital output pin 1 of DAQ card.

Rule 9: If T is greater than 0.15 Nm and T_R is greater than 200% Then send the message "Stop the process immediately." and Send the pulse signal to Digital ouput pin 1 of DAQ card.

Rule 10: If F_R is greater than 200% and T_R is greater than 200% Then send the message "Stop the process immediately." and Send the pulse signal to Digital output pin 1 of DAQ card.

Rule 11: If F_R is greater than 400% Then send the message "Stop the process immediately." and Send the pulse signal to Digital output pin 1 of DAQ card.

Rule 12: If T_R is greater than 400% Then send the message "Stop the process immediately." and Send the pulse signal to Digital output pin 1 of DAQ card (Table 2).

Table 2 Default values and operator defined values

Operator define values	Recommended value for (KHSS-E)	Recommended value for (HSS-E)
Force limit for response 1	200 N	120 N
Torque limit for response 1	0.15 Nm	0.08 Nm
Force limit for response 2	400 N	150 N
Torque limit for response 2	0.2 Nm	0.1 Nm
Force Ratio for response 1	2	2
Torque Ratio for response 1	2	1.5

The number of rule may be much larger amount when the process is more complicated, the fuzzy base system can be applied to be easy to solve such the complication.

4 Tool life test in deep hole drilling

4.1 Experimental setup for tool life test in deep hole drilling

In addition to the storage signals, the new tool life test has also been carried out in this project. Two kinds of drills are tested with same material (HSS-E) but one is with coating (TiN) and the other one is without coating (Dominguez and DeMiguel Gonzalez 2002; Landers and Ulsoy 2002; Kirchheim and Wlfer 1998; Pontuale et al. 2001). The diagram in Fig. 7 roughly illustrates the experimental set up. In Fig. 7, the two measurement platforms can be seen easily. Two measurement platforms are set up in tool life test, one is with sensors and other one is just dummy platform without mounting any sensor. In sensor platform, the Acoustic Emission sensor is mounted at the workpiece directly and the dynamometer for the purpose of measuring the thrust force and torque signal is installed under the workpiece. The reason of setting up two different platforms is to be able to avoid the very large storage file size for all of the signals along the tool lifetime experiment.

4.2 Strategy of collecting the signals

The process is conducted in grouping method, 25 boreholes in one group. First 7 boreholes out of 25 are drilled on the sensor platform and the rest 18 boreholes are drilled in the dummy platform. As previous measurements, the thrust force, torque and A–E signals are recorded (Carr 1988). The next part will describe the analysis of Torque, Thrust Force and AE signal for the tool life test.

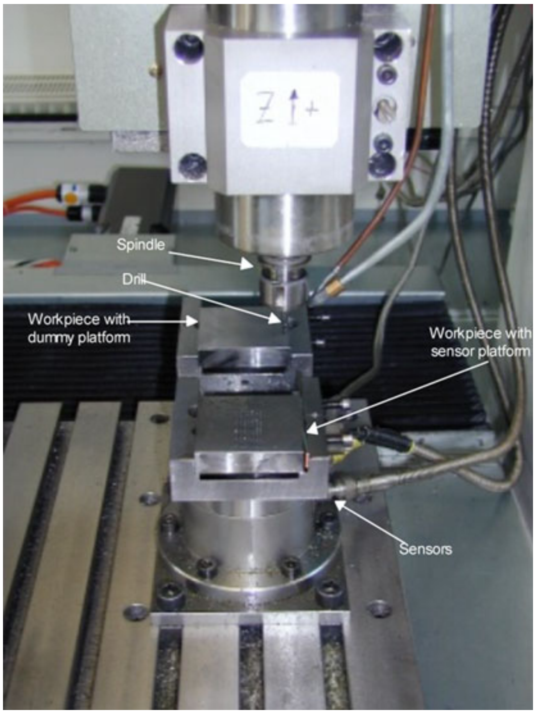

Fig. 7 Experimental setup with two platforms for the tool life test

4.2.1 Tested drills: drill no. 05

Figures 8 and 9 show the torque signal analysis of drill no. 05 measurements. The first figure describes the peak, average and standard deviation of each borehole. And the second figure is done after smoothing by grouping in 10 boreholes and averaging again, but this grouping method is done by shifting. The last two figures, Figs. 10 and 11 have been done in the same procedure as thrust force signal (Table 3).

5 Results of tool life test

Based on the aforementioned information regarding the general characteristics of thrust force and torque, the tool

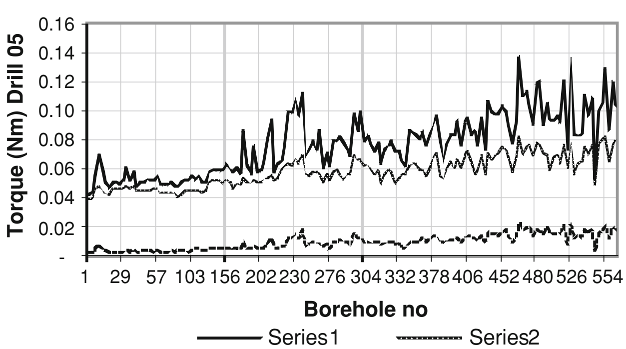

Fig. 8 Torque signal analysis without smoothing, drill no. 05

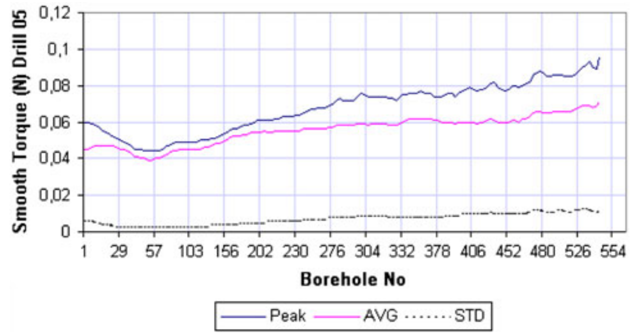

Fig. 9 Torque signal analysis with smoothing (group length 10)

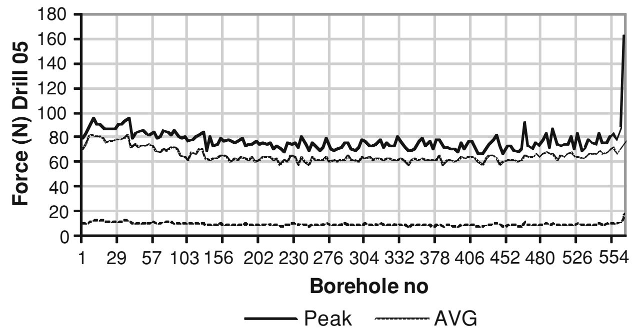

Fig. 10 Force signal analysis without smoothing, drill no. 05

Table 3 Drill 05 test parameters

Diameter	1.5 mm
Material	HSS-E, uncoated
Workpiece	C45, 10503
Borehole depth	12 mm
Pilot borehole depth	3 mm
Filter	Lowpass
Cutoff frequency	5 Hz
Tool life	Drill breakage at borehole no 557
Cutting travel	6.684 meter
Lubricant	Minimal lubricant machining 18 ml/h of minimum lubricant supply to the cutting zone/tool.

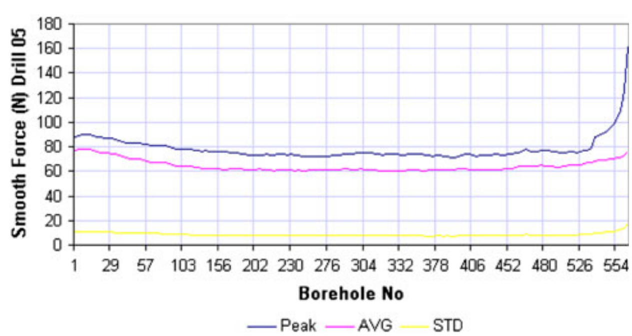

Fig. 11 Force signal analysis with smoothing (group length 10)

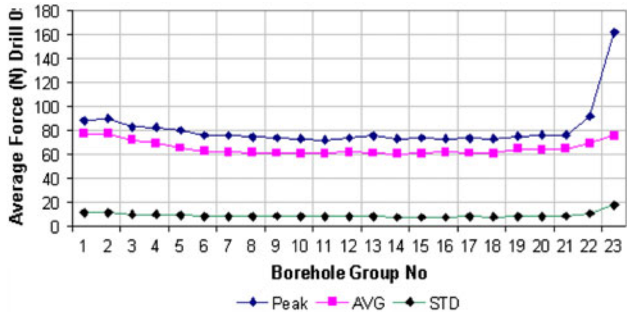

Fig. 12 Average Force in grouping drill no 05

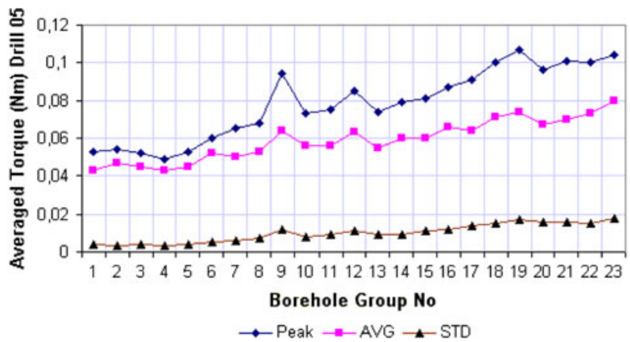

Fig. 13 Average Torque in grouping drill no. 05

wear condition can be investigated (Bishop 2001). In this test, it is found that the torque signal features can be reliable than thrust force, see in torque and thrust force analysis figures. The peak value curve, average value curve and standard deviation curve show the gradual increase up to approximately 0.12, 0.08 and 0.02 Nm, respectively, at borehole no 557 of drill no. 05. By increasing the group length, the feature curves can be getting smooth and the correlation of toque and tool wear can be clearly visible in this front panel.

5.1 Evaluation of analyzed features

Additional calculations have been done for extracted features. It was clearly found that the Torque signal is more influenced to the drill wear status, see Fig. 12. These graphs were created in group no in the *X* axis and the average amplitude in the *Y* axis. The signals from 25 borehole cycles are collected in one group and the average value is calculated for each feature as presented in the Fig. 13.

6 Conclusion

At the beginning of this project, the proposed monitoring system, shown in Fig. 1, is described in project. It was mentioned to use the API (Application Programming Interface) of OpenCNC utility to integrate the monitoring system to the machine which is illustrated in dotted line in Fig. 1. However, after the monitoring program has developed, the alternative possibility has been found that the hardware communication to interface between DAQ device and OpenCNC machine. So this part is replaced by hardware connection by using the function of DAQ device in Digital input output channel 0 and channel 1.

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