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The intelligent on-line monitoring of end milling

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Abstract

The main topics discussed in this paper include sensor integration, data extraction, data processing, monitoring the cutting tool, safety of the tool machinery, and quality of the components in processing. The detection method used in this paper is to extract the workload of a spindle motor from a CNC controller, and then transmit the data via a I/O card for further processing. The computer is connected to the CNC by DNC and is able to detect abnormal conditions and transmit, through DNC, to CNC the NC program to stop the machine or to replace the cutting tool. The systematic architectural instrument develops tools with object-oriented professional software and establishes software structure using a visual component library. The software component structure is made easy for maintaining and extending programs and for the operating system with its graphics user interface. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Sensor integration; Monitoring; Cutting tool; Quality processing

1. Introduction

During various cutting processes, breakdown and wear and tear of the cutting tool causes inferior quality of the components in processing, and suspension of the production line which reduces productivity. Therefore, one of the critical phases of production automation is to monitor the cutting tool on line and ensure timely replacement of the cutting tool if necessary. It should, in this way, guarantee the components' quality in processing and increase the system's reliability. A crucial development goal is to enable the system to operate for extended periods of time without human supervision or intervention while providing the same high quality components. The basic abnormality detection of the cutting tool relies on the monitoring technology for cutting. The common goal is therefore to develop reliable and effective detecting methods and technologies.

The mere monitoring of the cutting tool is effective. As computers are getting ever faster, the application of human intelligence and integration of neural networks and fuzzy logic into multi-sensor fusion have delivered significant results. Most scholars have done research in such areas as monitoring wear and tear of cutting tools by the signals of cutting power [1–4], study of statistical vibration indices obtained from the signals of spinning speed and electric current of spindle during cutting [5–9], introduction of neural networks to monitor the cutting tools and development of intelligent monitoring technologies [10–14]. The traditional monitoring methods are already mature and in use after years' of research and efforts by many scholars. However, intelligent monitoring creates the new trend even though it is still too expensive to popularize. We should therefore, with inverse thinking, aim to reduce the costs of an intelligent monitoring system but achieve the same effects.

2. Architecture of the system

The software of the monitoring system can be roughly divided into four parts:

1. I/O Input: I/O Port data reading and the following calculation, and saving the results in buffer.
2. Rules and Judgment: selection of appropriate rules based on parameter settings, judgmental calculation, and explanation of results using explanation mechanism.
3. Explanation Mechanism and Telecommunication

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Transmission: display of judgment results and transmission of NC program by DNC.
4. User Interface: Windows 98 standard graphic interface.

Windows Explorer systematically classifies and saves the data extracted and the relevant parameters. Most expert system software cannot provide an external interface for I/O extraction modules to plug in. Therefore, Borland C++ Builder Version 4.0 is used to set up the intelligent cutting tool monitoring system based on Microsoft Windows 98 platform. This architectural instrument develops tools with object-oriented professional (OOP) software and uses a visual component library (VCL) for software structure. The software components are structured in such a way that makes it easy for program maintenance and extension and with the graphics user interface (GUI), easy for users to operate the system.

The detection method used in this system is to extract the workload of the spindle motor from the CNC controller, and then transmit the data via the I/O card for further processing. The computer is connected to CNC by DNC and able to detect abnormal conditions and transmit, through DNC, to CNC the NC program to stop the machine or to replace the cutting tool.

Window function transmits the requested data from PMC to CNC. In the meantime, we can also receive data at CNC or change the data received at CNC. When the byte of the data to be transmitted G200.0 is different from the byte of the data transmission completed F250.0, CNC will send out the requested data. The CNC controller determines if the internal transmission is correct or not by calculating the inverse of numerical data of G200.0. The related control code parameters need to be set up before data transmission between PMC and CNC is allowed. They are:

1. Functional Number: to use binary to set the parameter G202;
2. Functional Type: to denote data transmission direction by different G200.1 values:
   CNC→PMC when G200.1 is set to 0 (output).
   PMC→CNC when G200.1 is set to 1 (input).
3. Data Length: to designate the length of the data to be transmitted (in unit of word) and to set the parameter G203 using binary.
4. Classification: to classify the data type to be transmitted in various function codes and use different classification codes in different function codes.
5. Data Transmission: to assign the location of the data to be transmitted in CNC. For input, G200~G209 is the transmission range; for output, F252~F267 is the transmission range.

When there is an error in implementing Window function, the error-detecting code (F250.1) will change from 0 to 1 as well as reverse the byte of the data transmission completed to indicate the failure of transmission. When the transmission process is completed, the error-detecting code (F250.1) will be set to 0 to indicate everything is normal.

Reading the motor workload of the FANUC controller is the 25th function of Window Function. The data type is binary; the data length is 1 word; and the data range is 0~32767. The control data are shown in Table 1.

The control data refer to the initial values of such functions as G202 set to be 25 and G203 set to be 1. These settings of initial values must be written in Ladder program on PMC. After the PC reads the data from the PMC, the PC must restore the data to Load (%) values.

The formula for restoration is [15]:

$$\text{Load}(\%)=\frac{L}{32767}\times\lambda$$

where L=value of data from PMC, λ=motor's maximum output factor. It varies based on the motor model. It is usually 150~180%.

3. I/O interface technology

The system is set up on the basis of Windows 98 application programs. Therefore it has to solve the problems with building an I/O port in a multifunctional system [16]. First of all, we need to know the architecture of Windows 95/98. Since Win32 API doesn't provide an application interface, an individual driver is required for the hardware to be controlled. Manufacturers do not provide a driver to the universal 8255 card. This system uses the driver components provided by Borland C++ Builder. No conflict or incompatibility with other drivers is found after testing for an extended period of time.

The voltage of direct current from the I/O B2 card is 24 V but the 8255 card accepts 5 V. Therefore photo-couple is used to isolate interfaces and convert voltages. When the I/O B2 sends signals, it transmits 5 V signals one on one to the 8255 card via photo-couple interface. The two ends of the interface are signals produced by photo-couple chips so that they do not affect each other and are even safer than the normal voltage reduction.

Table 1
The default information of Windows function no. 25

G202	Functional number	25
G203	Word number of data	1
G204	00	0
G205	00	0

Table 2
The DNC communication control code in FANUC controller

Character		7	6	5	4	3	2	1	0
DC1 0×11	Tape reader start	0	0	0	1	0	0	0	1
DC2 0×12	Tape punch designation	0	0	0	1	0	0	1	0
DC3 0×93	Tape reader stop	1	0	0	1	0	0	1	1
DC4 0×14	Tape punch release	0	0	0	1	0	1	0	0

4. DNC technology

The introduction of DNC enables this system to integrate with CNC tool machinery completely. In normal operation, DNC transmits NC programs. When the system detects any abnormality of the cutting tool, it inserts programs to replace the cutting tool. Of course, the length of the cutting tool must be rectified beforehand. Only in this way can the automation of this system be accomplished such that this system would be able to run without human supervision or intervention. The completion of DNC requires two technologies. One is conversion of the NC program to ISO code or EIA code. The other one is RS-232C transmission technology. They will be discussed further as follows.

4.1. Conversion technology

There are usually two coding formats for CNC tool machinery to receive processing programs. One is EIA (Electronic Industrial American) code. The other one is ISO (International Standard Organization) code. Personal computers mainly use the ASCII (American Standard Code for Information Interchange) code. Therefore the ASCII code needs to be converted into ISO or EIA code before being transmitted to the CNC controller for execution (the Fanuc controller uses ISO code). In addition, data transmission by PC and CNC is semi-dual functional communication of the ISO code. CNC defines some communication control codes as shown in Table 2 to notify the computer of the receiving conditions in order to avoid data loss or overflow.

Transmission usually follows certain orders as demonstrated in Fig. 1. When the tool machinery is switched into DNC mode, the CNC controller will continuously send DC1 control code to signify that the current temporary memory is empty and wait for the NC programs sent by the computer. When the temporary memory is almost full, the CNC controller will send out the DC3 control code to tell the computer to suspend the transmission so as to avoid errors resulting from full memory. The CNC controller will sound the alarm then stop the machine. During DNC transmission, the two codes of % and LF must be sent first to inform the CNC controller that the program is ready to be transmitted. Every single byte of the program ends with LF. When the transmission of NC program is completed, % is sent to notify the CNC controller that the DNC communication is finished.

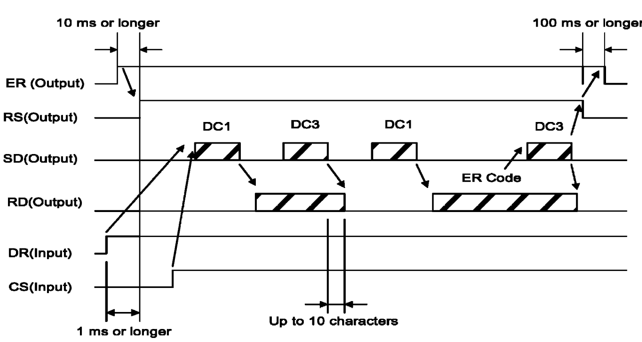

Fig. 1. DNC data transmission order representation.

4.2. RS-232C transmission technology

The RS-232C interface meets industrial standards, which makes technology extraction easy. Now we discuss how to integrate the interface into the whole system. In Windows 98, there are two ways to support the serial port. Firstly, since the serial port is the standard equipment, the operating system provides Win32 API services. The serial port can be used as soon as API is called in the program. Secondly, the hardware driver is used for the purpose of serial port control. The first one is easier for operation but leaves the threading problem unsettled. Windows 98 is a multifunctional system. Every program or part of a program has a threading, which makes it possible that the operating system can simultaneously execute programs in turn to realize multifunction. In the programs of this system, DNC interface will freeze in the process of I/O extraction and the related calculation. Therefore threading must be added to the RS-232C transmission program. The monitoring system with multi-threading can run every single part of the program simultaneously based on job division as well as monitor and transmit the jobs.

5. Experiment equipment

CNC milling machine: Victor Machinery Vcenter-65. The CNC controller is FANUC 0-M series.

I/O B2 Extension Card: DI/DO=144/122. The plugs are FANUC standard sockets such as M61, M62, M78, M79 and M80 etc.

Photo-couple Interface: I/O-01, I/O beta version, of total 24 inputs.

Personal Computer: Pentium 133, 32 MB Ram, 850 MB Hard disk.

8255 Card: 8255 dual-interface testing card, of total 48 I/O points.

In addition, the cutting tool used in the experiment is ϕ10 HSS-Co ending milling cutter, and the cutting material is S50C carbon steel. Fig. 2 shows the architecture of the system.

6. Experiment planning and testing

6.1. Slot milling testing

In slot milling testing, the cutting distance is about 260 mm. The load is about 1~2% before cutting and increases to 13% when the tool cuts materials but soon comes back to a stable level of about 11%. The cutting test shows when cut in the material with high feed (speed) rate will produce signals of vibration up and down. Fluctuations happening during the milling process indicate that the cutting tool is easy to break in high-

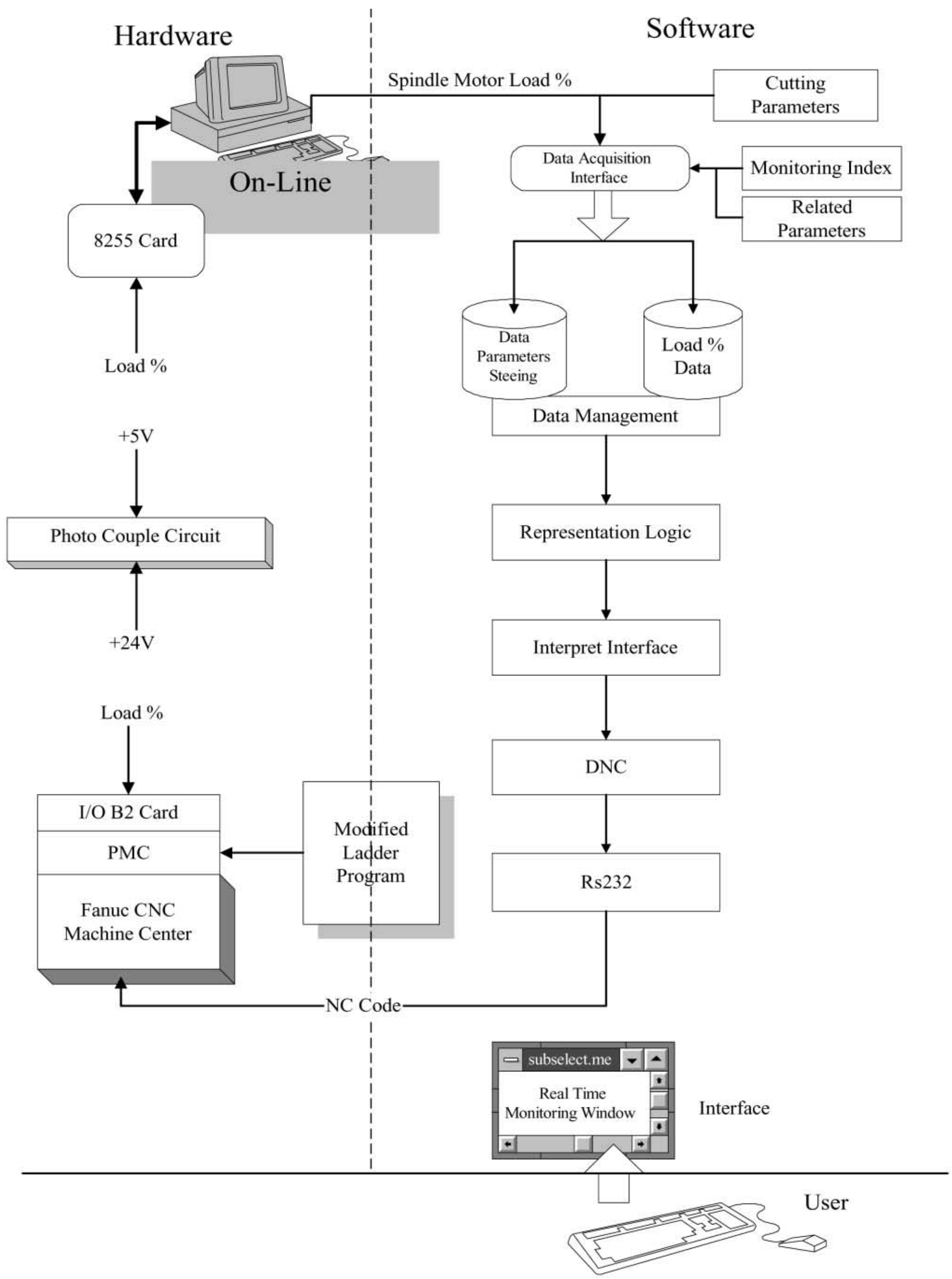

Fig. 2. System architecture and functions.

speed cutting. To sum up, the ϕ10 ending milling cutter, either brand new or worn and torn, brings a range of 1.5~2% vibration to the motor's workload.

6.2. Zig–Zag cutting

The slot cutting distance is too short to learn the complete course of the cutting tool being from brand new to unusable, so Zig–Zag cutting is applied to parts processing. The cutting conditions are changed to S=1875 rpm, F=300 mm/min. The cutting depth is the same as 3 mm. Ending milling by ϕ10 makes serious wear and tear to the cutting tool or even breaks the tool when it reaches 246.5 cm in depth in milling. The results from the experiment indicate that Zig–Zag cutting changes cutting direction, in which course it loses 1~3% power. Since Zig–Zag changes direction in cutting action, it produces temporary fluctuation. The motor is characterized by its extraordinary sensitivity to any sudden change of workload.

We used the data collected to analyze the spindle motor's complete course of cutting by a brand new tool until the tool is so worn and torn to be unusable. The trend of the signals seems somewhat strange because it reflects the piecewise properties of the change of workload with ups and downs. The workload will increase due to the wear and tear or damage to the tool. When it goes above the vibration range of 1.5%, noise comes out. The ups and downs of the workload can mainly be attributed to the fixed power of the spindle motor. The wear and tear of the tool makes the workload fluctuate first, then increase followed by a decrease to a stable value. Any relatively big unusual movement in the process should be a momentary result from the damage to the tool.

The reasons for changes are identified: I/O B2 sends data to the PC once every 16 ms while the spinning speed of the motor is 1875 rpm. Every revolution takes 0.032 s. The end-milling cutter has two blades so the cutting time for each blade is 16 ms. It means that in every 16 ms there is one blade using its power to cut. Although the data are not obtained when the power is either maximum or minimum, in other words, when the tool cuts the thickest part or withdraws from the component, the data would still be able to appropriately reflect the conditions when the tool is worn and torn. When the tool is brand new, the difference between the cuts by each blade should be small. The cutting depth would be different when the blade breaks. The workload would then be different too. The maximum change of workload may be 2~4% when a blade is damaged. The workload fluctuates by 1.5% when the tool is worn and torn. This information could be used as monitoring indicators.

7. Establishing monitoring rules library

Based on the data obtained in the previous section, the initial values do not show any consistent trend. However, the workload did increase later on, which could be used as a rule for judgment. According to the observation of the data, when workload exceeds 8~15% above that of the normal processing operation, it signifies that the tool is close to breaking point.

The motor is more elastic to sudden changes. Hence the change in this reaction could be used to convert the initial data to workload variable δ then multiply it to obtain δ^2. The square values of the data augment the vibration range beyond 1% and narrow the vibration range less than 1%. In other words, they magnify the abnormal signals. δ^2 is an important monitoring indicator in this system. When the abnormal δ^2 reaches the warning limit, it indicates that the tool is unusable and the CNC tool machinery should be instructed to replace the cutting tool or stop. By the same token, the workload fluctuation indicator δ^2 generated by the wear and tear of the blades of the cutting tool also provides a rule, within the time scope Δt, to detect vibration and sharp noise in cutting. This rule is applicable to the cases where the cutting tool is not brand new.

To sum up, the following three rules are derived from the above:

1. if (Load % $>\Delta$) then (stop the machine)
   Δ: δ Load % determined by the diameter of the cutting tool.
2. if ($\delta^2>$ Indicator _1) then (count 1)
   OR(AND) if($\delta^2>$ Indicator _2) then (count 2)
   OR(AND) if($\delta^2>$ Indicator _3) then (count 3)
   OR(AND) ….
   If (count 1 OR count 2 OR count 3 OR …)$<$Threshold then (stop the machine)
   Indicator _x: degree of damage to the cutting tool
3. if ($\Delta t>\Delta T$)
   AND if(δ^2 number$>$Threshold) then (stop the machine)
   Threshold: warning value given
   ΔT: length of time period given

8. Experiment results and verification

8.1. Experiment 1

To use a set of cutting tools for Zig–Zag milling. Tool: ϕ10 HSS-Co double blade end-milling cutter; Material: S50C; Cutting conditions: S: 1875 rpm, F: 300 mm/min, cutting depth: 3 mm, and dry cut.

Parameters Set-up and Outputs Explanation Mechanism

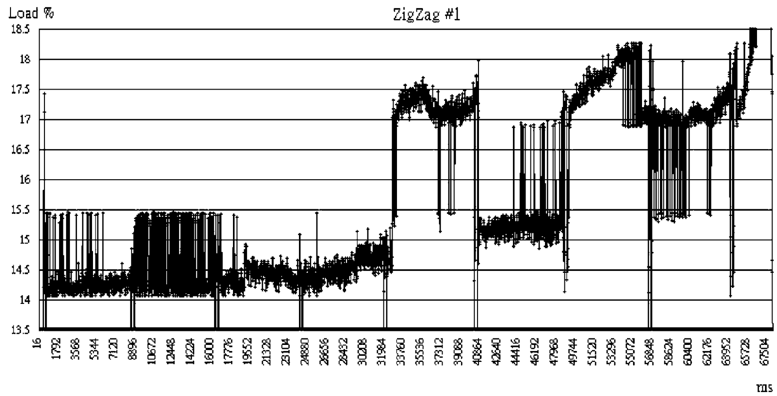

Fig. 3. The cutting data from test 1.

Rule 1: Δ=10% indicates the cutting tool is about to break.
Rule 2: When $\delta^2 \leq 1$, the output is set to 0 to indicate normal and stable cutting.
When $1 < \delta^2 \leq 2$, the output is set to 0.3 to indicate the slight damage to the tool.
When $2 < \delta^2 \leq 3$, the output is set to 0.5 to indicate the mild damage to the tool.
When $3 < \delta^2 \leq 4$, the output is set to 0.8 to indicate the severe damage to the tool.
When $\delta^2 > 4$ the output is set to 1.0 to indicate that the tool is probably about to break or already broken. It could also be a noisy signal, but can be corrected by learning process.
Rule 3: ΔT: 500 ms
Threshold: continuously accumulated 10 values
It indicates the generation of sharp noise and vibration thus severe damage to the cutting tool.

8.2. The results from Experiment 1

The cutting information for the first cutting tool is displayed in Fig. 3. A total of 4207 observations were received after the noisy information was filtered. The data were converted into monitoring indicator δ^2, as shown in Fig. 4.

Fig. 5 lists the initial cutting information for the second knife under the same cutting conditions. The converted monitoring indicator δ^2 is shown in Fig. 6.

The results are acceptable for testing and verification. However, when to notify the CNC tool machinery to stop is determined by the judgmental rules and accumulative warning values. For example, in the original testing file, the numbers of the monitoring indicators for various conditions of the cutting tools were:

When the monitoring indicator was equal to 0, training data were 4724 groups.
When the monitoring indicator was equal to 0.3, training data were 331 groups.
When the monitoring indicator was equal to 0.5, training data were 108 groups.
When the monitoring indicator was equal to 0.8, training data were 29 groups.
When the monitoring indicator was equal to 1, training data were 16 groups.

The values between 0~0.3 indicate normal and stable cutting. The values above 0.5 indicate that the change of motor's workload exceeds 1.4% thus the cutting tool is probably already damaged or worn and torn. The values above 0.8 indicate abnormal cutting. Therefore, the accumulated number of indicators could be used as

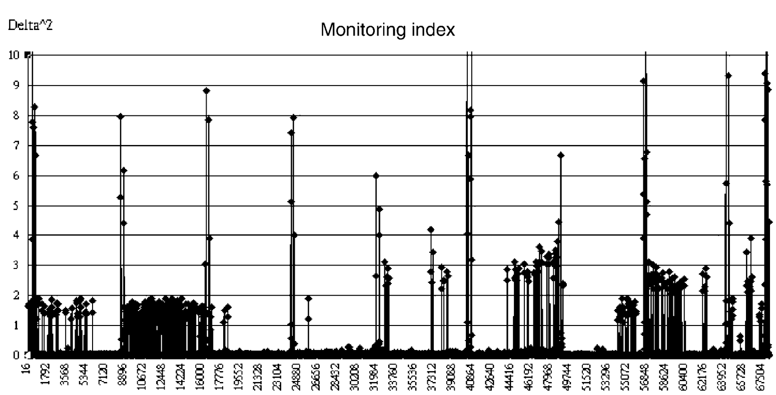

Fig. 4. Converting the first cutting data to monitoring index.

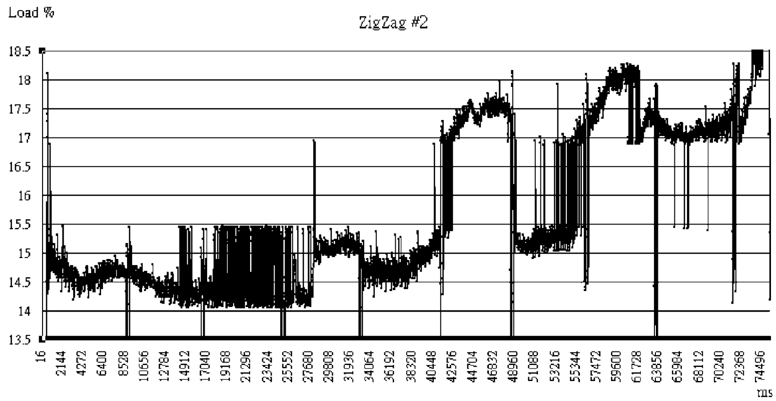

Fig. 5. The cutting data from test 2.

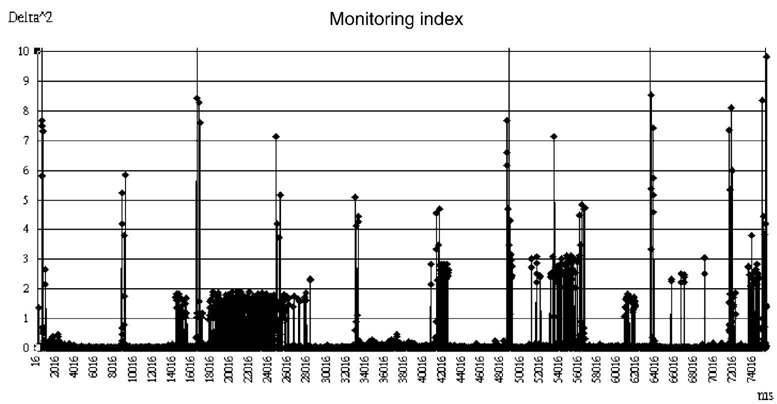

Fig. 6. Converting the 2nd cutting data to monitoring index.

a warning line. The selected range is a critical determinant of prompt replacement of the cutting tool. Since this rule applies to a projective method, it needs to multiply by an adjusting value referring to a safe factor.

The third level of warning is determined by the sum of the result of the number of the monitoring indicator 0.3 of the first group of data, multiplied by an adjusting value referring to a safe factor (0.5~0.8), and the result of the number of monitoring indicator 0.5 multiplied by (0.5~0.6). The monitoring indicator of 0.8 is the second level of warning. And the monitoring indicator 1 could be abnormal conditions or noisy information. It makes the first level of warning when it multiplies by an adjusting coefficient with respect to a safe factor (0.3~0.6). When the second and third level of warnings reaches the selected warning limits, DNC will send the NC programs to replace the tool or stop the machine. The first level of warning is more dangerous, so the order will be issued to stop the machine once the warning limit is reached.

In the monitoring simulation using the second group of data of the cutting tool, Rule 1 was intercepted when the workload increased to 24% and the cutting tool broke when the workload rapidly rose to 30%. The results of Rule 2 were intercepted by the first level of warning limit. The third level of warning limit accumulated up to 85% close to the boundary and the second level of warning limit accumulated up to 83% close to the boundary. The results above testified that this system could certainly detect any abnormality of the cutting tool in time. If looser warning limits were chosen, the rules would not have successfully intercepted. In other words, the selection of warning limits is crucial to the rules. The selection method is to filter the extracted data and then multiply by a safe factor. Rule 3 counted by $\delta^2>1\sim1.5$. When $\delta^2>1\sim1.5$ is detected, the timer should then be turned on immediately. If it accumulates up to the warning limit within ΔT, then the warning will be sent out or interception will start.

8.3. Experiment 2

To use a set of cutting tools for Zig–Zag milling. Tool: φ10 HSS-Co double blade end-milling cutter; Material: S50C; Cutting conditions: *S*: 1500 rpm, *F*: 285 mm/min, cutting depth: 3 mm, and cut it dry. The purpose of the experiment is to test this system under the cutting conditions with a few changes, hoping to reduce the costs of establishing the rules library.

Since the system in this paper converts the change variable of workload δ into monitoring indicator δ^2, the system should be able to work under the cutting conditions with a few changes. It is not necessary to gather data of workload under different cutting conditions for knowledge extraction. Therefore this experiment will process under different cutting conditions but judge the extracted data using the rules in the knowledge library from the previous experiment. Moreover, this experiment will initiate the on-line function and transmit NC programs by DNC.

Due to the changes of the cutting conditions, it is predictable that the life of the cutting tool will be prolonged. The warning limit will be extended beyond the limit of the first group accordingly. How much to extend is projected on the basis of experience but restricted within the component processing scope. Zig–Zag cutting requires more times of change of direction. As a result, the impact of change of direction needs to be estimated. We assume that the life of the cutting tool can be increased by 1.5 times, then the warning line is set by adding the number of the first group to the result from multiplying the 1.5 times of the number of the first group by the minimum level of the safe factor.

This system reached the first level of warning limit when it successfully received no. 4985 group of data. For the purpose of the experiment, the cutting continued until no. 5991 set of data was received and the tool was completely unusable. We learned by simple calculation that the limited changes of cutting conditions could still successfully intercept before the tool was damaged. It has thus proved that this system could largely reduce costs by reading the motor's workload.

9. Conclusion

The monitoring indicator used in this paper is defined based on the reaction of the spindle motor's workload to cutting conditions. It works with other rules to accumulate abnormalities. When the abnormalities are accumulated to the given warning limits, the cutting tool will need to be replaced. The experiments have proved that appropriate selection of warning line is very important. The experimental costs are lower if abnormal signals can be identified under slightly different cutting conditions. A great deal of literature has realized that single sensors couldn't clearly reveal the cutting conditions. Yet it costs from a hundred thousand to a million to purchase such sensors as dynamic meters, AE sensors, torsion-force-based moment sensors. In knowledge processing, knowledge rules can easily be, by expert system, added and developed to a graphical user-machine interface, which makes it easy for users to operate.

The simple calculation can effectively intercept at a point before the cutting tool breaks and replace it with a brand new cutting tool. However, in the widely applied processing by end milling, a certain number of experiments may be needed for various processing methods. The statistical data are further summarized to deduce the most conservative warning range under various processing circumstances. The results are collected in a database and included into this system so that they can be given directly as suggested values for later use. In case that this system is not a multithreading program, if any single module is overloaded, it will cause other modules to stop, especially when receiving judgment. As this system is changed to a multithreading program, the problem can be solved. Due to the improvement of Internet technologies, this system can add the communication means of TCP/IP by which the cutting information can be sent to the remote main control room. If abnormalities happen, engineers will be sent to take care of the problems upon notification or the NC programs processed by Cam will be sent to the computer and given to this system using DNC connection.

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