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Cutting tool condition recognition in NC machining process of structural parts based on machining features

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Abstract

Cutting tools are direct performers in material cutting processes of NC machining, while the degree of cutter attrition and breakage directly influences the quality of production. Meanwhile tool condition recognition is a key technique in automatic and unmanned machining process. Aimed at this problem, the recognition of tool-condition based on machining feature in real-time is stated. Machining features are used to build relationships between geometry, processing technology and monitoring signals in order to provide the basis for cutting tool condition identification. A feature database is established with experimental results and a cutting tool condition recognition system is established based on this database. Experimental results suggested that the proposed method solves the problem of tool condition monitoring, especially for production with multi varieties and small-batches.

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1. Introduction

With the increased application of high-performance numerical control machines, NC machining has got fast development, and lots of structural parts are processed by them. NC machining processing is the key factor affects quality of workpiece which also impacts machining cost [1]. During a machining process, we have to keep an eye on the equipment situation when it's running and change the tool if find it broken. Actually, cutting tools wear during the machining processes, and will not satisfy the machining requirements [2]. However the judge of tool condition mainly depends on experiences of workers at present. So if we want to reduce the number of workers and implement automated production, we have to guarantee the cutting tools wear in a permissive range.

As we all know, the cutting tools experience three stages from a new one to a scrapped one: initial worn stage, normal worn stage, acutely worn stage, as shown in Fig.1 [3]. In order to avoid the problems of processing quality and safety, cutting

tools must be changed when it reaching segment of acutely worn [4]. At present, a cutting tool is changed based on the amount of using time in most manufacturing companies, which cause resource waste or machining quality decline [5]. Moreover many aircraft structural parts have thin-walls and large size, which led to more complex machining conditions, and more difficulties in the monitoring of cutting tool condition [6].

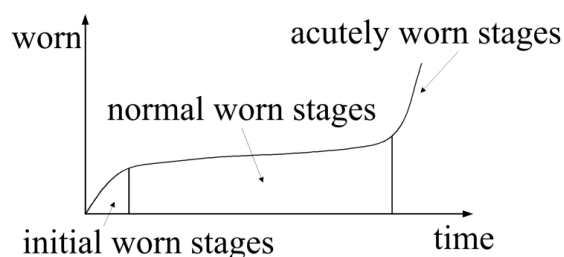


Fig.1. stages of tool wear

In conclusion, a method should be presented for cutting tool condition recognition, which could remind workers to change cutting tools according to the real operation. The down time of cutting tool malfunction will also be shortened to get higher machining efficiency. At the same time, the implementation of tool condition recognition is the base of intelligent manufacturing.

2. Literature review

To deal with tool condition recognition problems, there are two methods, forecasting method and monitoring method. And the monitoring method includes direct ones and indirect ones.

A forecasting method is a technology that extrapolates tool-failure time by scientific methods when a tool is under normal condition [7]. The purpose of this method is telling people when we should replace a cutting tool. The forecasting method builds a tool life prediction model by simplify a cutting process [8]. It is under an ideal condition. So, its biggest problem is that it only applies to specific condition. The prediction model failures when the cutting parameters change.

A direct monitoring method judges tool condition by measuring the wear of a tool directly. This method is the most direct and most accurate one. It includes contact monitoring method, radiation detection method and computer image processing method. Among them, the contact monitoring method uses contact sensors. It measures the cutter diameter before and after a machining process when a machine tool is stopped. And it uses the differences of cutter diameter to judge the tool condition. This method must stop a machine tool and cannot find out suddenly damages. A radiation detection method uses radioactive substances which are harmful to humans and the environment, and it is no longer been used. A computer image processing method uses optical instruments to get images of tool wear zones [9]. It uses these images to judge the tool condition by pattern recognition technology. This method seriously affects by chips and coolant [10]. In general, a direct monitoring method cannot detect suddenly damages and can only be used in specific conditions.

An indirect monitoring method judges a tool condition by indirectly signals which related to tool wear. The signals used by this method include cutting force signals, vibration and acoustic emission signals etc [11, 12]. Scientists use time-domain analysis method and frequency-domain analysis method or time-frequency analysis method for handling the signals we get, like averages, Fourier transform and Wavelet transform etc [13]. After the original data acquisition, signal processing and time-frequency domain analysis, scientists judge the tool condition in pattern recognition [14].

An indirect monitoring method is mainly suitable for tool condition judgment in large quantities production and is not suitable in small quantities production or single piece production. The methods that are designed to work for different cutting conditions need some sort of training before the actual cutting process. If any process variables change, system retraining becomes necessary.

Currently there are some commercial products available for tools and machine condition monitoring. Factories can choose these products to improve machine utilization and reduce production cost.

ARTIS system is a system which used in all kinds of metal cutting machine tools and production lines for monitoring process and machine condition. Its task is to protect tools, optimize cutting process, reduce cost and optimize production and quality. It has different sensors for different monitoring signals. This system is very suitable for turning process. But in milling process, it encounters problems of wrong alarms.

Forecasting Method only applies to those specific conditions. There are a lot of limitations because the prediction model failures when the cutting parameters change. A direct monitoring method cannot detect suddenly damages and can only be used in some certain machining conditions. The indirect monitoring method and the commercial product cannot deal with tool condition recognition very well in small quantities production or single piece production. So there is necessary to find out a method of tool condition recognition in small quantities production or single piece production.

3. The overall of the proposed method

Normally, NC machining parts have the characteristics of large size, complicated structure etc. But even the most complex parts can still be decomposed as a combination of multiple features through analyzing (feature—geometry with a certain engineering semantics) [15, 16]. In STEP AP224, ISO has defined some typical geometric feature structures including pocket, boss, hole, step, profile etc. For example, the complex structural part in Fig.2 can be decomposed as a combination of several pockets, holes, ribs and profiles.

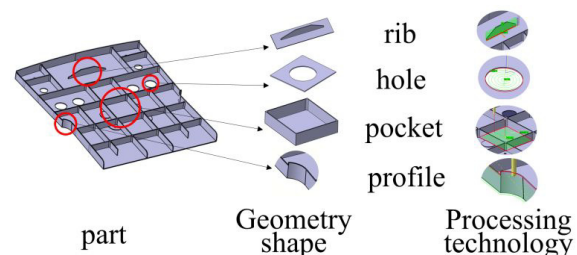


Fig.2. Complex parts can be decomposed as a combination of features

The process technology of a part is complicated, but for a certain geometric feature, the processing technology is relatively fixed. The right part of Fig.2 is the processing technology of some typical features like rib, hole, pocket and profile. For a particular structure, its machining parameters can be fixed and inherited because of factories' standard production and processing.

The above two points can provide a new idea for cutting tool condition recognition in a NC machining process of aircraft complex structural parts, which is the method of tool condition recognition based on feature in this article. The

feature here refers to geometry with a certain associated processing technology. For example, ‘pocket + 20mm flat bottom tool + circular feeding way + feed speed 1000mm/min + spindle speed 3000r/min + cutting depth 1mm + cutting width 1mm + Aluminum material’ is a feature. ‘hole + 20mm flat bottom tool + circular feeding way + feed speed 1000mm/min + spindle speed 3000r/min + cutting depth 1mm + cutting width 1mm + Aluminum material’ is another one.

Main idea of this method adopted by this article is as follow. Select typical features and take experiments before actual parts machining. Record monitoring cutting force signal and calculate the monitoring signal threshold. On this basis, establish a feature monitoring database. During the machining process, determine which feature is being machined and judge the tool condition by comparing with different monitoring thresholds in the feature database according to different features. If a cutting tool is broken, this system warns immediately and reminds operators to stop machining and change cutting tools. It should be pointed out that the monitoring signal adopted here is not limited to a cutting force signal. It can also be a vibration signal, etc.

4. Feature based tool condition recognition system

4.1. Feature based monitoring threshold database

Feature database is the basis of comparison and judgment in machining process. It needs to select typical geometric features according to experience before actual machining. Take 10 groups experiments using typical processing technology to create feature database. Pocket, hole, rib, profile are selected as geometry according to the characteristics of the aircraft structural parts in this article. The selected cutting parameters are the common ones in factories. Firstly, do the experiments with a normal cutting tool. Measure cutting force values and record data (the monitoring signal measured here can also be vibration signal or spindle power signal etc.). Use the following formula to get the monitoring signals’ average value, mean square value, variance and peak value.

$$\bar{X} = \frac{1}{N} \sum_{i=1}^N x_i \tag{1}$$

$$X_{ms}^2 = E[x^2(t)] = \frac{1}{N} \sum_{i=1}^N x_i^2(t) \tag{2}$$

$$\sigma_x^2 = \frac{1}{N} \sum_{i=1}^N (x_i - \bar{x})^2 \tag{3}$$

$$X_p = \frac{1}{n} \sum_{j=1}^n x_j \tag{4}$$

At this time, each value has 10 sets of data. After getting rid of the maximum and the minimum of these 10 sets of data, the value of average is calculated. Accordingly, the treated average value, mean square value, variance and peak value is computed. These 4 values make up a 1*4 vector P_n . Then, the Euclidean distance Ω_n between vector P_n and original point (0,0,0,0) is calculated.

As the same, repeat the experiments above with a worn tool, the Euclidean distance Ω_m between vector P_m and original point (0,0,0,0) could be calculated. The monitor threshold Th could be calculated by the formula below.

$$Th = \left| \frac{\Omega_n - \Omega_m}{\Omega_n} \right| \times 100\% \tag{5}$$

This threshold should be stored in the database with geometric structure, machining parameter, parts material and tool information. The data are extracted from the database and calculated in the following recognition process. The record contents of database are showed as Table 1 to Table 3. In feature database, the detailed shape includes the straight path (marked 1) and the circular path (marked 2).

Table.1.Feature Database

No.	Geometrical shape	Detailed type	Tool number	Processing technology	Parts material	Monitor threshold
1	001	1	001	001	002	6.7
2	001	2	001	001	002	10.3
3	002	2	001	002	003	5.4
...

Table.2.Tool information Database

No.	Type	Diameter	Teeth number	Material
001	End mill	10	4	Hard alloy
002	Face milling cutter	100	14	Hard alloy
...

Table.3.Processing technology Database

No.	Spindle speed	Feed rate	Cutting width	Cutting depth
001	2000	2000	1	1
002	3000	1000	1.2	1
...

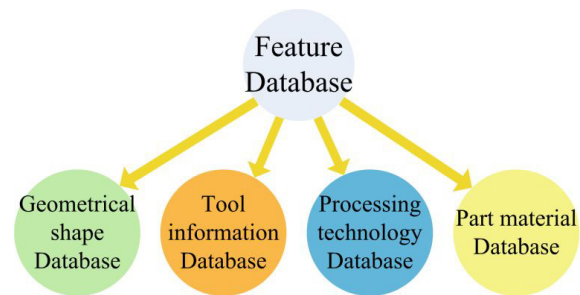


Fig.3.The structure of feature Database

Actually, the feature database contains geometrical shape database, tool information database, processing technology database and parts material database (shown as Fig.3). A geometrical shape database includes numbers and geometrical shape of the features (pocket, hole, tip, profile, etc). A parts material database includes numbers and material name of a part (steel, aluminium, titanium, etc). All these databases

connect each other by key words for demand. In the actual machining process, matched through monitor flags added in NC codes, the related threshold contracted from the database participates in the recognition of the cutting tool condition.

4.2. The identification of machining features in NC code

The purpose of adding the monitor flags in NC codes is to judge how to choose different threshold according to different features in the process of tool condition identification. The precondition of this work is that the tool path and the NC code have already generated. During toolpath edition, use annotation to mark some programs and establish an identity of general feature. After generating NC program, this annotation appears in NC code. Those lines of NC codes below this annotation are associated with this machining feature. This annotation is the monitor flag of a machining feature (showed as the line A in Fig.4). ‘TH’ is a flag using to distinguish with normal NC code. The roles of those digits are as follow: ID of geometrical shape, mark of Detailed type (0 is a mark of entire machining feature), ID of cutting tool, ID of processing technology, ID of parts material.

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%1000
N1 G49 G54 G64 G40 G90 G20 G94 G17 G80
N2 G53
N3 T1 M6
N4 ; TH 001 0 001 001 002
N5 G0 X16.4024 Y58.3002 S70 M3
.
.
.
TH 001 start
N25 X28.1491 Y65.4024 Z-2.
N26 X27.4714 Y65.4687 F1000.
N27 G3 X24.5314 Y62.5287 I0 J-2.94
TH 001 1 001 001 002
N28 G1 Y37.4714
TH 001 2 001 001 002
N29 G3 X27.4714 Y34.5314 I2.94 J0
.
.
.
N862 G3 X42.0599 Y79.9999 I-2.94 J0
TH 001 end
.
.
.
N866 Z50.
N867 ; THP 002 14 CR20 R5 3000 2000 2 5
N868 G0 X73.8775 Y20.8056
N869 G1 Z5.5
.
.
.
    
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Fig.4.The working NC code

The tool path of approach, machining, retract and the cutter location points could be extracted by software like CATIA. According to the order of machining, the last cutter location point of approach tool path is the start point P1 where the tool contact the surface of a part, and first location point of retract tool path is the point P2 where a cutting tool leave the surface

of a part. After finding the location of these two points, extract the coordinates in each line of NC code one by one. Compare those coordinates with P1 and P2, and then the code contains P1 and P2 could be found. The monitoring process begins with ‘TH 001 start’ and finishes with ‘TH 001 end’, which will be added before those two lines of codes. The ‘001’ mentioned above is the number of current feature (showed as the lines B, E in Fig.4).

In addition, there are two kinds of tool path in the process of pocket, rib top and profile machining. One is a straight path. The other one is a circular path. All of them should be marked in the NC code. Line C in Fig.4 is a monitor flag of a straight path and Line D in Fig.4 is a monitor flag of a circular path. The roles of those digits in these monitor flags are the same as described above. The machining features are distinguished by these monitor flags. According to different features, there are different threshold in feature database.

4.3. Cutting tool condition recognition

When a machine process begins, the cutting tool condition recognition system finds the monitor flags by a query. If the system gets a flag like ‘TH 001 start’, it starts acquiring signals. If the system gets a flag like ‘TH 001 end’, it stops acquiring signals. During the process of getting signals, the system compares the flags in NC code with the flags in feature database and find out the same one. Then it gets a monitoring threshold-*Th*. According those signals, the treated average value, mean square error, variance and peak value are computed. These 4 values make up a 1*4 vector *P_i*. Then, the Euclidean distance Ω_i between vector *P_i* and original point (0,0,0,0) is calculated. The monitor threshold *T_i* could be calculated by the formula below.

$$T_i = \left| \frac{\Omega_n - \Omega_1}{\Omega_n} \right| \times 100\% \tag{6}$$

Compare *T_i* with the monitoring thresholds *Th*. If *T_i* < *Th*, it means the tool is in a good condition. If *T_i* > *Th*, it means the tool is broken. The machine process should be stopped. And the tool should be replaced.

5. Experimental Verification

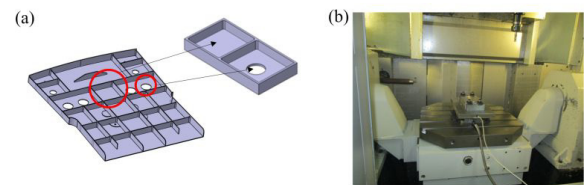


Fig.5.(a)Part model; (b)Dynamometer installation

The part shown in Fig.5(a) is used as an example to verify the proposed method. The part contains a pocket and a hole which are typical geometrical features in a complex structural part. The dynamometer installation in experiment is shown in Fig.5(b).

5.1. The selection of sampling Parameters

In experiment, the highest spindle speed is set as 6000r/min, frequency 100Hz. The lowest spindle speed is set as 600r/min, frequency 10Hz. The signal frequency of expected machining status is under 16 times frequency. Use Kistler 9443B dynamometer as the signal acquisition instrument. Sampling rate f_s is set as 4000Hz, and sampling point is set as 1024.

The highest analysis frequency is

$$f_{\max} = 100 * 16 = 1600 \text{ Hz}$$

The sampling interval is

$$\Delta t = 1/f_s = 1/4000 = 0.25 \text{ ms}$$

The sampling length is

$$T = N * \Delta t = 1024 * 0.25 = 0.256 \text{ s}$$

The frequency resolution is

$$\Delta f = 1/T = 1/0.256 = 3.9 \text{ Hz}$$

5.2. The experiment result

Taking Labview2014 as a basis, a feature-based tool condition monitoring system has been developed. In order to verify its performance of tool wear condition identification, normal tool and worn tool are used respectively for machining with the same cutting parameters. Fig.6 shows the operation result of machining by a dull tool. The system alarms and reminds that the tool is wear, CNC machine tool should be stopped immediately and the cutting tool should be changed. The experimental accuracy rating reaches to 95%.

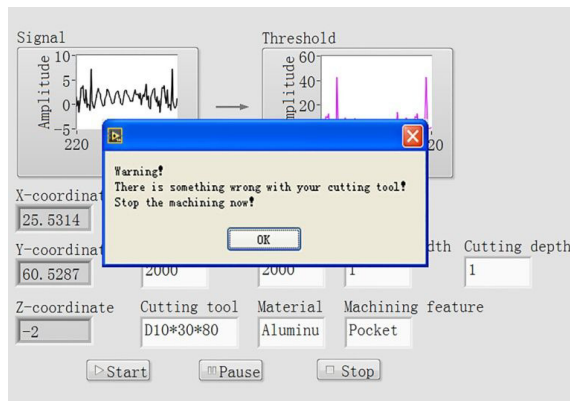


Fig.6.Experimental result of the test part

6. Conclusion

This paper investigated the requirement of manufacturing companies. A feature-based tool condition recognition system was developed to address the difficulties of tool condition monitoring in milling process of structural parts. The system is tested by using a part with a pocket and a hole. The

experimental results suggested that the proposed method can solve the problem of tool condition monitoring, especially for the production with multi varieties and small-batches.

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