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Condition assessment for automatic tool changer based on sparsity-enabled signal decomposition method

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ABSTRACT

Automatic tool changer (ATC) is one of the key basic parts in CNC machining centers, and the globoidal indexing cam and the groove cam are the functional units for tool changing. Thus the condition monitoring is important for highly efficient and precision machining. In this paper, a condition monitoring system is constructed for the ATC, especially for the globoidal indexing cam, including vibration signal acquisition, fault feature extraction and localization, and condition assessment. In the constructed system, sparsity-enabled signal decomposition method is introduced to extract transient component and reduce noises in the complex vibration signals, and the transient component is always a key feature for fault localization. Simulation study shows that the sparsity-enabled signal decomposition method is effective in transient feature extraction. The experimental application in condition assessment for the ATC demonstrates that the constructed condition monitoring system has the potential to assess the working condition of the ATC in practical application.

1. Introduction

CNC machining centers develop towards the direction of high efficiency, high precision, high speed and multi-function, which means CNC machining centers should have the comprehensive machining ability, such as milling, drilling, boring and tapping. It is necessary to carry out the sequential tool change between the tool spindle and the tool magazines while machining the complex workpieces. Thus, automatic tool changer (ATC) is one of the key basic parts in CNC machining centers to implement automatic tool-changing which is the essential difference between the terms machining center and milling machine [1,2].

Advanced CNC machining centers can efficiently change tools within a short time interval of a second, which is mainly achieved by the ATC with a combined cam, including a globoid indexing cam for rotation and a groove cam for axial movement. Because of the frequent tool changing of the CNC machining centers while manufacturing complicated parts, the working condition of the ATC will decline inevitably. Eventually, the performance of the CNC machining center will degrade. In order to ensure the machining quality, the ATC should work without malfunction. Thus, the condition monitoring and assessment for the ATC are of great importance.

The localized fault on a rotating component will produce a series of impulses that may excite vibration responses in the mechanical system, which can be measured by a transducer at a nearby location on the casting of the machine [3–5]. Thus vibration monitoring and signal analysis is an effective method for condition monitoring and assessment [6,7]. Since the ATC consists of a globoid cam, a groove cam, gears, bearings, driving shaft, etc., the vibration signal will be mainly composed of two components, i.e., periodic transient component and oscillated harmonic component, and both of them will be masked by background noises. As the periodic transient component is always excited by a localized fault in a rotating part, the transient feature extraction is an effective method for condition monitoring and assessment for the ATC.

During the past decades, many signal processing techniques have been widely studied for fault feature extraction in the area of machine fault diagnosis [8–10], such as wavelet transform (WT) [11–16], time–frequency analysis [17–19], empirical mode decomposition (EMD) [20–22], and independent component analysis (ICA) [23,24]. The WT provides the information of analyzed signals in the time and frequency domains simultaneously through a series of convolution operations between the analyzed signal and a predetermined wavelet basis [25]. Since the WT is a constant Q-factor filter, if the basis wavelet is selected properly, it can match well with transient component (or harmonic component) through shifting and scaling and therefore transient component (or harmonic component) can be effectively extracted [26–28]. However,

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the selected basis wavelet is only effective in representing one component (transient component or harmonic component). Time–frequency analysis method is similar to the WT, and has similar shortcomings. The EMD is an adaptive decomposition technique for nonlinear and non-stationary signals through decomposing complicated signal into a set of intrinsic mode functions (IMF). It has been developed and widely studied in vibration signal analysis [20]. However, in some cases it may reveal plausible characteristics due to the mode mixing, which makes it untenable in transient extraction. The ICA attempts to decompose a multi-component signal into independent non-Gaussian signals. The effectiveness of the ICA decomposition of multi-component signals is based on two assumptions: source components are independent of each other, and the distribution of each component is non-Gaussian. In mechanical systems, the measured signals are the convolution of the excitation sources and the transfer paths. The excitation sources may be independent; however, they may have similar transfer paths. Moreover, the number estimation of the excitation sources in mechanical systems is a challenging research [29].

Recently, sparse representation-based methods began to be studied for machine fault diagnosis because of its ability to extract the fault feature accurately, such as compressed sensing based transient extraction [30], matching pursuit based impulse extraction [31], sparsity-enabled signal representation [32,33], and crack growth sparse pursuit for wind turbine blade [34]. Considering the fact that the vibration signals of the ATC are mainly composed of periodic transient component and oscillated harmonic component, and both of them will be masked by background noises, the sparsity-enabled signal decomposition method [35] is introduced to separate the different components and reduce the effect of noises in the present study. Firstly, the morphological component analysis (MCA) [36] is used to construct the objective function for signal decomposition, in which two tunable Q-factor wavelet transforms (TQWT) [37] with different parameters are incorporated to sparsely represent the different components to overcome the shortcoming that each wavelet transform cannot provide sparse representation for different components simultaneously. Then the problem of signal decomposition is turned into the minimization of the objective function which is solved by the split augmented Lagrangian shrinkage algorithm (SALSA), and this is the second procedure of the sparsity-enabled signal decomposition method. These two procedures can realize the signal decomposition and noise reduction.

The remainder of the paper is organized as follows. In Section 2, the principle of the ATC is reviewed, and the condition monitoring system is proposed for fault localization and condition assessment. Then, the key signal analysis method in the proposed condition monitoring system, i.e., sparsity-enabled signal decomposition method, is presented in Section 3. Section 4 provides a simulation study and comparison to verify the effectiveness of the proposed method. In Section 5, the proposed condition monitoring system is applied in the fault localization and condition assessment for the ATC. Finally, conclusions are drawn in Section 6.

2. Principle of ATC and condition monitoring system

2.1. The structure and principle of the ATC

The ATC in the CNC machining center is a unit which allows machining centers to change tools to realize different machining processes automatically. Fig. 1 provides a partially broken plan view of a cam-driving ATC. The combined cam including a globoidal indexing cam and a grooved cam is the key element of the ATC. The rotation and the axial movement of the tool-changing arm are mechanically worked together by the combined cam mechanism so that the tool-changing arm may be operated quickly and smoothly.

The ATC is driven by an electric motor with a constant speed via the input shaft, and then the rotation of the input shaft is transmitted to the combined cam via a helical gear. The globoidal indexing cam and the grooved cam serve as a rotating cam and a movement cam, respectively. When the globoidal indexing cam is rotating, the tool-changing shaft and the tool-changing arm is rotated by the follower roller. Simultaneously, as the result of the rotation of the groove cam, the follower roller is moved along the cam groove so that the swing lever is swung, then the tool-changing shaft and the tool-changing arm is axially moved forward and backward by the engagement roller engaged with the engagement groove of the tool-changing shaft. The rotation and the axial movement of the tool-changing arm can realize the tool changing. Fig. 2 shows the five steps for tool changing. Firstly, the ATC receives the order of changing tools, rotates to the specified location, and simultaneously grips two tools, the operating tool in the spindle and the tool to be used next in the tool magazine. Then the tool-changing arm is driven by the grooved cam to remove the tools away from tool magazine and the spindle, which is followed by a 180° rotation driven by the globoidal indexing cam to exchange the position of two tools. The forth step is to insert the tools into the tool magazine and the spindle. The last step is to reset tool-changing arm to its initial position.

Fig. 3 provides the displacement diagram of the ATC. In Fig. 3(a), the segments *ab*, *cd*, *ef*, and *gh* correspond to the non-rotating state of the tool-changing arm. The segments *bc*, *de*, and *fg* indicate the rotating state with 65° in the counter-clockwise direction, 180° in the counter-clockwise direction, and 65° in the clockwise direction, which correspond to griping, exchanging and resetting process in Fig. 2, respectively. In Fig. 3(b), the segments $a'c'$, $d'e'$, and $f'h'$ indicate the tool-changing arm has no axial movement. The segments $c'd'$ and $e'f'$ indicate the rising and falling process of the tool-changing arm which correspond to the removing and inserting processes in Fig. 2, respectively.

2.2. The condition monitoring system for the ATC

To monitor the condition of the ATC, a condition monitoring system was constructed, as shown in Fig. 4, which includes a signal acquisition system, 4 accelerometers, and a laptop. The vibrations of the globoidal cam-driving ATC are collected by 4 accelerometers mounted on the housing of the ATC. Moreover, the flow chart of the vibration signal analysis for fault diagnosis and condition assessment is also provided in Fig. 4. Since the ATC has a complex structure, the measured vibration signals consist of not only the vibration of globoidal cam but also the vibration of groove cam, helical gears, rolling bearings, etc. For example, the state change of the tool-changing arm gives rise to impulses, localized faults in the cam also induces impulses at the same time. Moreover, these impulse responses are mixed with the harmonic components caused by some rotating elements and noises. It is important to extract and distinguish the impulse from vibration signals for condition monitoring. Therefore, the sparsity-enabled signal decomposition method is introduced to separate the different components and reduce the noise effect. Considering that the cams run in accordance with their displacement diagrams, the impulses caused by the state change of the tool-changing arm will also be identified with the displacement diagrams. It means that the abnormal impulses caused by the localized faults can be distinguished from the normal impulses caused by the state change of the tool-changing arm, thus the fault can be located. Furthermore, if the abnormal transient component is selected to calculate quantitative fault features, these features can be used as the feature index for assessing the condition of the globoidal indexing cam.

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