Rotate Vector Reducer Crankshaft Fault Diagnosis Using Acoustic Emission Techniques

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Abstract—Rotate Vector (RV) reducer is widely used in robotics because of its high precision and stiffness. However, the long-term operation leads to unpredictable reducer failures due to the inevitable abrasions of mechanical parts. To this end, this paper is intentionally designed to diagnose the RV reducer crankshaft abrasion faults using acoustic emission (AE) techniques. Firstly, the AE signal features with various speeds and workloads are extracted and analyzed in both time domain and frequency domain. Secondly, the crankshaft abrasion effects are qualitatively evaluated using these time-frequency features. Extensive experiments are conducted on our built RV reducer robotic platform. The experimental results prove that our method is able to effectively detect RV reducer crankshaft faults.

Keywords—RV reducer; crankshaft fault diagnosis; acoustic emission

I. INTRODUCTION

The RV reducer is one of the most critical mechanical parts of industrial robot manipulator. During the operation, RV reducer transmits the power from the servo motor to the linkage \cite{3} by converting the high speed and low torque of servo motor to low speed and high torque of output shaft. However, during the robotic long-term operation, the malfunction of RV reducer may cause severe decline of product accuracy, which is more obvious in the robotic arm that features in the cascade architecture. In the state of art, the abnormal RV reducer operation states are monitored using temperature sensors in normal routine maintenance. However, industry robot manipulators are mostly used in assembly line such as in car industry. The assembly line will be shut down when a sudden failure occurs, which will cause enormous losses.

Generally, to collect and analyze the reducer states is the main approach to detect the fault, but the disadvantage lies in its belated detection, i.e., the RV reducer has pervasively affected the normal operation when the faults are detected. In comparison with vibration signal analysis, acoustic emission technique is able to identify the fault in terms of both detection accuracy and response. Acoustic emission has the advantage of monitoring the fault evolution process during the earlier diagnosis \cite{1}. Compared with vibration based fault detection methods, AE has the following advantages: 1) it is robust to mechanical structural resonances and roughly unaffected by typical mechanical noise; 2) it is more sensitive to fault activities; 3) it provides good trending parameters \cite{2,4}. Because of these aforementioned merits, AE has been widely applied to pressure vessel, machine manufacturing, stress measurement at oil field and many other fields \cite{5-10}. However, few researchers have applied acoustic emission techniques to robot manipulator joint reducer fault detection.

The AE sensor is able to detect the stress wave that propagates inside the material and on the surface of the material when strain or crack occurs. Then the sensor monitor will localize the transverse wave and longitudinal wave corresponding to the crack part. Through this way, the cracks will be detected at early stage.

![Fig. 1. Layout of sensors](image-url)

Unfortunately, AE sensors have also some inherent drawbacks such as random attenuation and reflection phenomenon. Henceforth, the sensor must be rigidly fixed to the specific place close enough to the source signal point. Likewise, we also directly place the sensor directly to the shell of RV reducer via magnetic adherence. The configuration of our system is shown in Fig 1. To the best knowledge of the authors, this is the first time that quantitative analysis of AE techniques has been given specifically to fault detection of RV
reducer crankshaft. The result clearly shows the variation tendency in different working conditions.

II. BASIC METHOD OF SIGNAL ANALYSIS

A. Time Domain

Before we analyze the signal we have acquired, we should determine the signal source. When we take the signal, we can see that the signal is one kind of sinusoidal signal and equally distributed in the timer shaft. So, we firstly seek where the sinusoidal signal comes from.

Because of the fact that the signal is equally distributed in timer shaft, the signal source needs to be one kind of circular motion. In RV reducer, there are mainly about six types of rotatory parts: input shaft, planet gear, crankshaft and its bearings, output part, fluted disk and roller pins.

In RV reducer, the input-to-output ratio is:

\[ k = 1 + \frac{N_{\text{planet}} \times m}{N_{\text{in}}} \]  

or

\[ k = \frac{N_{\text{planet}} \times m}{N_{\text{in}}} \]  

where \( N_{\text{planet}} \) is the planet gear number of teeth, \( m \) is the number of the shell number of pin, \( N_{\text{in}} \) is the number of input shaft number of teeth. Formula (1) works on the condition that the shell is fixed and formula (2) is fixed on the output inner frame. These two formulas show the relationship of each part of the reducer, and there is one rotation subassembly which is the rotation of two fluted disks (shown in Fig 2), the fluted disk does circular motion by the internal of the shell’s pin. The shell and two fluted disk center of circle are placed on one straight line all time; the AE signal of crankshaft is propagated to the AE sensors through the fluted disk impinge on the shell internal pin.

B. Frequency Domain

FFT method is widely applied to AE signal analysis. It is one of the basic approaches to acquire the signal features. In this part, we use FFT to find the frequency distribution of the AE sensors acquired data.

C. Spectral Kurtosis

Kurtosis is able to measure the tailedness or skewness of the signal, rather than the peak of the signal. Kurtosis is the fourth standardized moment defined as

\[ K(X) = \frac{E[(X-u)^4]}{(E[(x-u)^2])^2} \]  

where \( u \) is the central moment of the series \( X \), and \( E \) is the expectation of \( X \). The kurtosis value of normal distribution is 3, when the value is less than 3, it means the data has fewer extreme outliers than normal distribution in statistics, and vice versa.

III. EXPERIMENT SETUP

A. Design of The Test Rig

The detection platform consists of three parts: test rig, drive motor and magnetic powder brake. The test rig is designed to simulate several working conditions for RMT-40E reducers. Motor data is collected at various speeds and working loads (shown in Fig. 2). The magnetic powder brake is used to offer linear load to cover the shortage of the lack of the torque sensor. The RV reducer system has the two-stage architecture: the stage of planetary gear speed reducer and a stage of cycloid-pin gear speed reducer (shown in Fig. 3). The difference between RMT and RV is the structure of fluted disc (shown in Fig 4), but for both of them, the transmission principle is the same. Because the structure of RMT’s fluted disc’s aim is to reduce the cost of production, the AE signal we monitored mainly comes from the crankshaft of cycloid-pin gear part (see the time domain analysis in detail), which has little influence on the experiment target. In our experiments, we set seven different rotatory speeds (400 rpm, 600 rpm, 800 rpm, 1000 rpm, 1200 rpm, 1400 rpm, 1500 rpm) and five levels of
workloads (set the magnetic powder brake exciting current at 0 A, 0.5 A, 1 A, 1.5 A, 2 A, when the current is at 5 A the load is approximately 1500 Nm).

B. Design of Signal Acquisition

The AE acquisition equipment has two data channels, both of which range from 100 KHz to 400 KHz. We set the sensors along the outer surface with the interval of 90° in both horizontal and vertical directions (shown in figure 1). In this way, we could detect the signal at different directions of propagation and find out the potential configuration differences. Through this way, we are able to not only find the propagation law of AE signal in reducer but find the better way to install the sensors from the perspective of engineering applications. Data acquisition system has several sampling rates (100 KHz, 200 KHz, 500 KHz, 1 MHz, 2 MHz and 5 MHz), we chose 2 MHz to be our sampling rate while considering both engineering practices and computational speeds.

C. Design of Experiment Step

In our experiment, the collected data are rotatory speeds and load torques, which are sampled before and after the overload tests. Each step has seven rotation speeds (400 rpm, 600 rpm, 800 rpm, 1000 rpm, 1200 rpm, 1400 rpm, 1500 rpm) and five load torques using five exciting current: (0 A, 0.5 A, 1 A, 1.5 A, 2 A).

Firstly, we took 35 groups of data at seven rotation speeds and five load torques; Secondly, we took 200 tests on overloads with field current 5 A, rotate speed 1000 rpm, input shaft rotatory circles 620 of). Likewise, we repeated the tests with seven rotatory speeds and five load torques.

Before analyzing the AE data, the data is preprocessed by cutting it into several patches, each of which is consistent with one circle of output shaft. The data length is given by

$$L = \frac{(60*k*r)}{v}$$

Where $L$ is the data length; $v$ is the rotate speed of input shaft; $k$ is reduction ratio, which we set 124 in this experiment. The coefficient 60 means the rotate speed is in the unit of minute; $r$ is the sampling rate, which is set 2000000 in this experiment.

IV. EXPERIMENTS RESULTS AND DISCUSSION

Three methods of data analysis were chosen to testify the feasibility of using AE for RV reducer fault diagnosis. Through the comparison of data analysis upon the before-overload test and after-overload test, we found several characters about the AE signal data at different working conditions.

A. Time Domain Analysis

Firstly, we plot the signal in one period (output shaft rotate one circle) and find that every period signal obviously has forty peaks of waves (rotation speed at 400 rpm, shown in Fig. 4). When the speed goes up, the peak number of waves increases. Based on the structure model we introduced in Section II, in every period of data, input shaft rotated at 124 circles; every crankshaft rotated at 41 circles; output shaft rotated at 1 circle. So there was no component which has the same frequency of 40. But in one period, there was 40 times that one of two fluted disc meet at one fixed point of the shell, which proved that our signal mainly comes from the contact between fluted disc and the shell (because AE sensor is installed on the shell). Since each reducer has two fluted disc, 80 peaks of wave in every period of waves is needed. After the overload test, we disassembled the reducer and found that the most abrasion part was on the crankshaft, the decrease of crankshaft diameter is 0.04 mm, the pin of cycloid-pin gear decrease is so little to calculate by micrometer.

B. FFT Analysis

The frequency range of AE sensor is [100 KHz, 400 KHz]; the resonant frequency was 150 KHz. We resort to FFT to analyze the data and find out the feature in range of 100 KHz-400 KHz, and we also analyzed the signal in range of 0 Hz-100 KHz because of its amplitude was high compared with...
the spectral among 100KHz-400KHz. We found that the AE signal we acquired was mainly from the friction of crankshaft, and the speed effect of the influence to the internal stress is higher than that of torque load (Fig 5 shows the comparisons among different rotatory speeds and torque loads by FFT analysis).

C. Kurtosis Analysis

![Fig. 6. FFT analysis in different rotate speed and different torque load (100KHz - 400KHz)](image)

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Table 1: Kurtosis value of AE data in different working condition
Lastly, we took the kurtosis to analyze our experimental data to find the variation tendency of our signal. Every period data kurtosis number was shown in Table 1. We took two steps in the following kurtosis analysis: 1) calculate the mean value of one rotatory speed in one working condition (such as all the data by 400rpm before overload tests) shown in Fig. 6a; 2) plot all kurtosis values in different rotatory speeds (Fig 6b – Fig 6h). We found that the kurtosis value variation range is small; kurtosis values are getting smaller while rotate speed increases; the kurtosis value after overload tests is smaller than that without overloads. Because the signal resembles sinusoid and the kurtosis is larger before the overload test; after overload test, the signal was become fierce, more fault signal was acquired and the amplitude was similar to the pear of the signal, so the kurtosis was decrease.

V. CONCLUSION

This paper presents an approach to detect RV crankshaft fault by measuring and analyzing the AE signals in both time domain and frequency domain. Theoretically, we proved that AE sensors could be applied to RV reducer fault diagnosis. From the process of analysis, we acquire some tendency of the signal in different working conditions.

In this experiment, there is no torque sensor, no angular transducer et al. The precision analysis of the signal and problem need to be increased. The analysis algorithm also need to be improved, these problem is our research direction of future.

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REFERENCES