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Research Article

A Novel Fault Diagnosis Method for Gear Transmission Systems Using Combined Detection Technologies

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Abstract: This study focuses on the condition monitoring and fault diagnosis of gear transmission systems. Since the gear transmission systems have been used in very wide applications, such as the aerospace engineering, manufacturing industry, marine engineering, etc., it is crucial to monitor the working condition of the gear transmission systems. For this purpose, a new method has been proposed in this study to investigate the condition monitoring and fault diagnosis of gear transmission systems. In the new method, the oil analysis and vibration analysis have been integrated to collect the fault signals of the gears. Then an intelligent classifier based on the Support Vector Machine (SVM) is adopted to diagnose the fault types of the gears. To verify the proposed approach, the fault experiments have been carried out in a gear fault simulator. The analysis results show that the lubricant information and vibration information can be well used for the accurate fault detection of the gears. The fault diagnosis rate reaches up to 91.7%. Hence, the proposed method can be used in practice for the condition monitoring and fault diagnosis of gear transmission systems.

Keywords: Condition monitoring, fault diagnosis, gear transmission

INTRODUCTION

Gear transmission is very important in rotating machinery and has been employed in variant industrial applications. However, due to harsh working condition, the gears often suffer from damages (Li *et al*., 2011a, b). Li *et al*. (2010) reported in their research that the accidents of rotating machinery caused by gear damages account for about 80%. Hence, it is urgent to monitor the operation condition of gears in the gear transmission system in advance to prevent damage events. Up to date, the oil monitoring and vibration analysis have been widely used in the condition monitoring fault diagnosis in academy and industry, due to the complexity of machineries, these two techniques only detect about 30 to 40% of faults if they are adopted independently (Peng and Kessissoglou, 2003; Peng *et al*., 2005; Li *et al*., 2012b). It is therefore critical to investigate the performance of the combination of oil analysis and vibration analysis in the fault diagnosis.

In order to combine the vibration analysis and oil analysis into the same framework, much work has been done by some scholars (Peng and Kessissoglou, 2003; Peng *et al*., 2005; Li *et al*., 2012b). On the one hand, the oil analysis can capture the wear condition features. Hence it can inspect the health condition through the inner side of the machines. As a result, the oil analysis can provide accurate and effective diagnosis for machines. On the other hand, a portion type of fault cannot be detected by oil analysis. Hence the vibration analysis is adopted to identify some abnormal behaviors of the machines using spectrum features (Li *et al*., 2012a, c). Useful vibration analysis approach include Empirical Mode Decomposition (EMD) (Li *et al*., 2010) and Wavelet Transform (WT) (Li *et al*., 2011b) etc. However, if these two methodologies are used independently, the detectable fault range is limited and hence leading to fake alarms in the fault diagnosis (Peng and Kessissoglou, 2003; Peng *et al*., 2005; Li *et al*., 2012b). Recent advancements in the integration of these two technologies indicate an increase detection rate (Mathew and Stecki, 1987; Peng *et al*., 2005; Chee *et al*., 2007; Li *et al*., 2012b). In these recent work the oil monitoring and vibration analysis have been combined to detect the undergoing failures in the mechanical systems. However, the combined detection method is seldom reported for the condition monitoring and fault diagnosis of gear transmission systems and effective diagnosis method has not been proposed. In such a situation, combined fault detection of gear transmission systems has become an urgent issue and received much attention. How to develop a use method to combine the oil analysis and vibration analysis to

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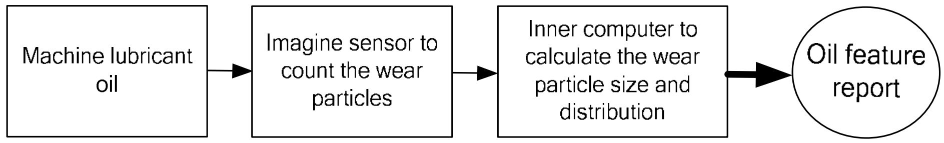

Fig. 1: The diagram of the oil monitoring detection

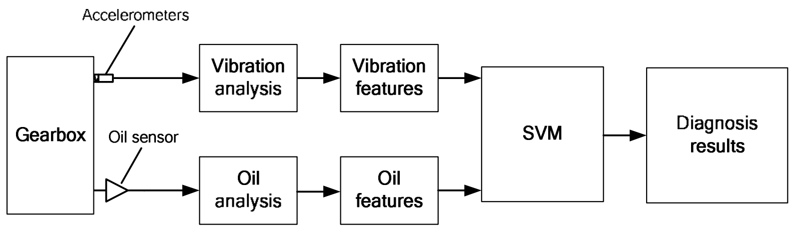

Fig. 2: The combination of oil analysis and vibration analysis

enhance detection performance of gear transmission systems becomes the hottest topical in the research field of fault diagnosis.

For the purpose of enhancing the fault diagnosis of gear transmission systems, this study presents a new fault diagnosis approach based on the combination of oil analysis and vibration analysis. The wear condition and body vibration information of the gear transmission under several faulty working conditions were recorded by an experimental test rig. The wear particle number and size distribution were extracted by the oil monitoring technology while the time and frequency features of the gears were obtained by the vibration analysis. Then, a support vector machine was employed as an intelligent classifier to recognize the operation conditions of the gears. The diagnosis results show that the proposed combined method is more effective for the fault diagnosis of gear transmission systems than separate use of the oil analysis and vibration analysis.

THE COMBINED FAULT DETECTION APPROACH

Since there is a potential advantage of combination of the oil analysis and vibration analysis to the fault diagnosis, we have established a new method to realize it in this study. The oil analysis and vibration analysis are integrated into one methodology and an efficient SVM classifier (Vapnik, 1995) is employed to recognize the fault patterns of the gear transmission system. Herein, the SVM adopts the kernel trick to make it be able to find the inherit relationship between the oil and vibration features and the fault patterns. The proposed combined fault diagnosis framework is briefly described as follows.

Oil analysis: Oil analysis aims to examine the lubricant oil of the machine so as to access their health level. In general, the lubricant oil contains a large amount of useful and original information about the wear condition of the machines. It usually adopts the ferrograph sensors to extract useful information which reflects the wear mechanisms and wear modes of the machines. The operation principle of the ferrograph sensors is expressed briefly as below.

From Fig. 1 it can be seen that the ferrograph sensors are kind of optimal devices and they have the ability to extract the size information of the wear particles suspending in the lubricant oil. Then, the extracted size information of the wear particles can be used an index to assess the wear condition of the machines.

Vibration analysis: Machines often break down with an obvious abnormal vibration. The vibration intensity and frequency are the most important features that indicate the health level or fault occurrence in a machine. Hence many advanced signal processing methods have been proposed to analyze the measured vibration signal to identify the vibrated related failures. Nevertheless, the most simple and effective methods are the traditional time series analysis (Li *et al*., 2011b) and FFT method. The useful statistics of the vibration signals are sensitive to the abnormality of the machines. These features include Root Mean Square (RMS), amplitude peak, skew and kurtosis.

The combination framework: The proposed integrated fault diagnosis method based on the oil analysis and vibration analysis is shown in Fig. 2. A special designed gear transmission simulator is used to evaluate the proposed method. The test set-up has been installed an oil ferrograph sensor and four accelerometers to record the oil and vibration signals, respectively. Then the oil features (i.e., wear particle size and distribution) and the vibration features (i.e.,

Table 1: The oil analysis results

Oil feature	A	B	C	D
Wear particle concentration (mg/L)	50~100	300~400	100~200	250~350
Wear particle area (μm^2)	100~300	400~800	150~200	20~40

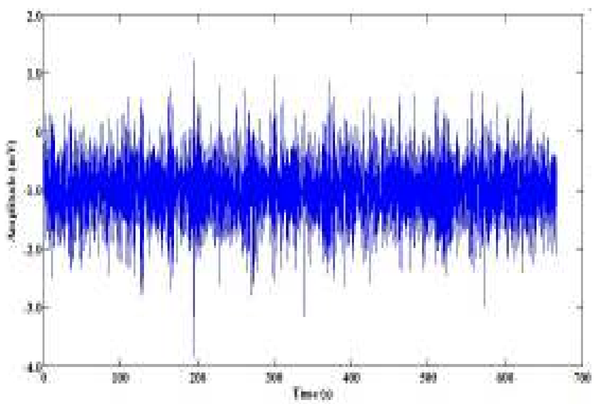

Fig. 3: The time series of the vibration signal of the cracked gear

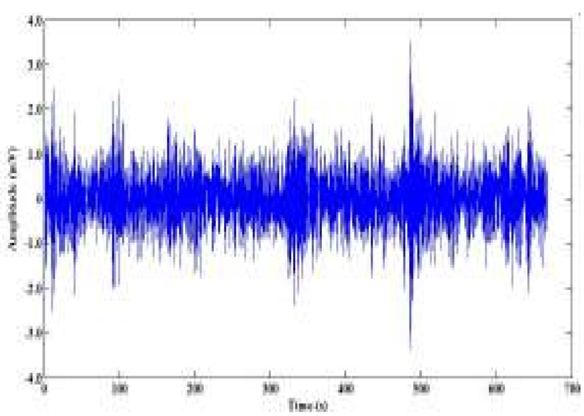

Fig. 4: The time series of the vibration signal of the broken gear

RMS, kurtosis, etc.) are extracted from the collected information. Lastly, the extracted oil and vibration features are treated as the input of the SVM for the pattern recognition.

EXPERIMENT TESTS AND RESULTS

The fault experimental tests have been carried out in the gear transmission simulator to evaluate the performance of the proposed combined fault diagnosis method in this study. In the experimental tests, man seeded fault has been imposed in one gear in the gearbox. The tested gear was tested under four operations: Pattern A-cracked gear, Pattern B-broken gear, Pattern C-worn gear, Pattern D-normal gear. The lubricating oil used SAE40, the shaft revolution speed of the tested gear was 500 rpm and the average room temperature was 22.0°C. The machine has run for 2 h each operation condition. The lubricating oil was collected every 10 min and 12 samples were recorded for each operation condition. The vibration signal was recorded every 10 min and 12 samples were obtained for each operation condition. The oil features about the wear particles were extracted. The oil analysis results are given in Table 1.

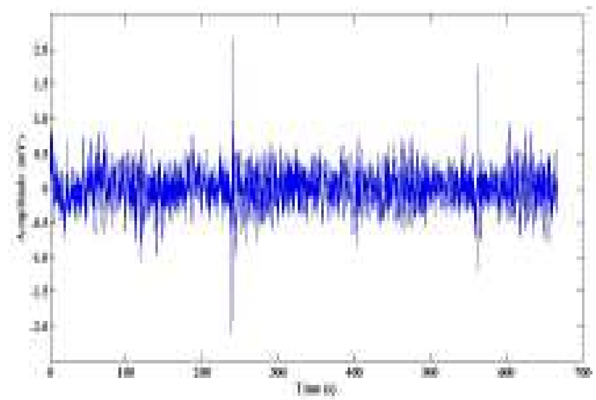

Fig. 5: The time series of the vibration signal of the worn gear

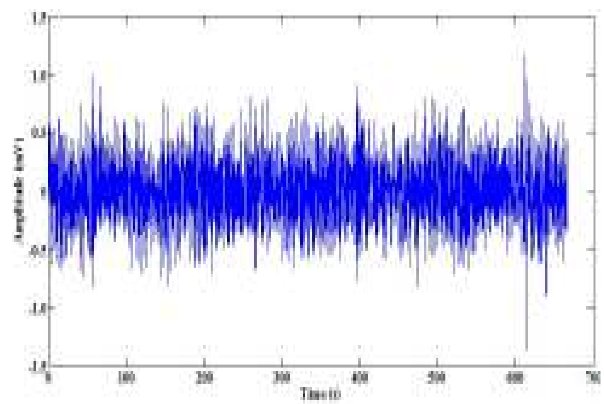

Fig. 6: The time series of the vibration signal of the normal gear

It can be seen from Table 1 that in normal condition, the area of the wear particles is smaller than that in faulty conditions, whilst the concentration size is bigger than others. The reason for this is that the normal gear may be in its running in stage and hence make relatively big wear concentration. However, since there is no failure in the normal gear, no faulty wear generates but normal small wear particles. In contrast, severe metal-to-metal contact occurs when faults appear and thus leading to a significant amount of abnormal size of wear particles. The oil analysis suggests that a failure has occurred if there is evident presence of large size particles. This suggestion would benefit the fault diagnosis in the pattern recognition.

Then the recorded vibration signals have been analyzed by time series analysis. The vibration signals of the four operations of the gear test set-up are shown in Fig. 3 to 6.

Table 2: The vibration analysis results

Vibration feature	A	B	C	D
RMS	155.2	137.6	157.4	215.4
Skew	11.3	12.1	10.4	8.7
Kurtosis	2.4	1.9	2.1	3.2

Table 3: The fault detection results using different methods

	SVM model	
Diagnosis method	Training	Testing
Oil analysis	79.2%	75.0%
Vibration analysis	75.0%	70.8%
Combined method	91.7%	91.7%

It can be seen from Fig. 3 to 6 that in normal condition, the amplitude of the gear vibration is smaller than that in faulty conditions. More importance, evident faulty pulse cycle peaks appear in faulty conditions. This is because that the faulty gear strikes the meshing movement of the gear pairs and hence generates the faulty pulse cycles and boost the vibration intensity. The vibration analysis suggests that a failure has occurred if there is evident presence of large vibration amplitude and cycle pulse impact. Hence the statistics of the vibration signals can provide useful information in the fault diagnosis. In this study, the RMS, skew and kurtosis values are calculated as the vibration features. Table 2 shows a portion of the vibration features.

It is noticed from Table 2 that the vibration feature values in the normal condition are evident different with the faulty conditions. In addition, these feature values vary with different fault types. As a consequence, it is possible to distinguish different faults using these features.

After the feature extraction, there are two oil features and three vibration features for each sample. Since oil monitoring and vibration monitoring have their own characteristics and scopes of application, respectively, we have combined them into a unified framework to enhance the fault diagnosis ability. A SVM classifier is employed to identify the operation states of the tested gears in this study.

As mentioned above, the feature space for all the samples is $F_{48\times5}$, where 48 are the total samples and 5 are the total features. In the fault pattern recognition, half of the feature space $F_{24\times5}$ is used to train the SVM and the rest for testing. As mentioned above, the combined use and the separate use of the oil analysis and vibration analysis are compared in the fault diagnosis in this study. Table 3 shows the fault detection results.

It can be seen in Table 1 that the performance of combination method in the fault diagnosis is much better than the separate use of oil analysis or vibration analysis. Owing to the integration of oil analysis and vibration analysis, the gear defection detection rate has been enhanced. This is because these two monitoring technologies have their own scopes of application and can learn from each other in mutual emulation if used jointly. As a result, the proposed combined method based on the oil analysis and vibration analysis has been proven to be powerful for the fault diagnosis of gear transmission systems. The fault detection rate is up to 91.7%.

CONCLUSION

Gear transmission systems are indispensable in modern industrial society. However, they often suffer from malfunctions. In order to prevent the gear transmission systems from damages, a new fault diagnosis method base on the integration of oil analysis and vibration analysis is proposed in this study. A series of experiments have been conducted in a gear transmission test set-up. The test results have demonstrated that comprehensive characteristics of the gear transmission system can be extracted by the combination method and the fault recognition rate is satisfied. The experimental test results show that the presented diagnostic approach is feasible and effective for condition monitoring and fault diagnosis of gear transmission systems. Further research can extend the proposed method to other complex machines.

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