論　文　の　要　旨

題　目　　Diagnosis of Gear Tooth Surface Damage by Analyzing Vibration Signal of Spur Gears

（平歯車の振動信号の解析による歯面損傷診断）

氏 名:　　范　青栄（D115756）

Gear device is one of the most commonly used and important components in machine system. Minor gear damage may cause serious failures of the entire equipment even huge economic losses. Consequently, it is crucial to detect the gear damage as early as possible to prevent the system from malfunction. Analyzing the vibration signal on gear or gear box is one of the effective methods to diagnose gear failures. Researchers have done countless studies in this respect and have developed many diagnostic methods based on the analysis of vibration signal in time domain, frequency domain and time-frequency domain. However, the diagnosis of gear damage in most widely used methods is usually based on observing the variations of characteristics between the normal gear and damaged gear. The diagnostic result mainly depends on the experience of operators and is unstable. Therefore, it is important to develop some technique for diagnosing gear damage with satisfactory accuracy independent of artificial experience.

This study proposes an intelligent method for diagnosing gear tooth surface damage by analyzing the vibration accelerations on gear box and bearing box. To investigate the validity of the proposed method, damage contrast test has been carried out in this study. Three kinds of gears, namely normal gear, spot damaged gear and pitted gear are tested under different loads and gear rotation speeds on the power circulating type gear testing machine. Moreover, in order to illustrate the progression of gear failures and to demonstrate the effectiveness of the proposed approach, the cyclic fatigue test also has been implemented on the power circulating type gear testing machine. A test gear is driven continually with the same rotation speed and load torque. During the cyclic fatigue test, the vibration accelerations on gear box and bearing box are measured at different cycles. Then, the technique of Fast Fourier Transform is used to analyze the characteristics of vibration signal in frequency domain. Frequency spectrum and residual signal are obtained using Fast Fourier Transform. After that, the method of discrete wavelet transform is employed to reduce the noise from residual signal. The processed signal is acquired by reconstructing coefficients of discrete wavelet transform. Additionally, in order to quantitatively illustrate the characters of vibration accelerations, statistical parameters and characteristic amplitude ratios of frequency bands are extracted from the vibration accelerations. Both of the characteristic amplitude ratios and statistical parameters are together served as failure feature vector for representing different gear conditions. Finally, the technique of support vector machine is employed to diagnose gear condition based on the extracted failure feature vector. In addition, another technique of empirical mode decomposition is adopted to extract failure feature vector for gear damage diagnosis. By the technique of empirical mode decomposition, the original signal is decomposed into several intrinsic mode functions. Then, the characteristic energy ratios are extracted from the intrinsic mode functions as failure features to be input to the support vector machines classifiers for diagnosis. The validity of the proposed approach is demonstrated by experimental results of cyclic fatigue test.

The following conclusions can be drawn from the previous performed work:

1. The large damage on tooth surface will cause transient larger abnormal amplitude in the original vibration signals, based on which the abnormal gear condition can be diagnosed. However, the abnormal amplitude is invisible when the damaged area is small. Therefore, the slight gear damage would not be detected based on the original waveform. In addition, along with the increase of gear rotation speeds and load torque, the vibration accelerations

become larger and the indication of damage also becomes more and more obvious in the original signal. The influence of varying loads in the vibration accelerations is weaker than the influence of varying gear rotation speed in the vibration accelerations.

2. The vibration accelerations gradually become larger and fluctuate more and more strongly as the increase of pitting area. Additionally, comparing with the normal teeth which have no failure on tooth surface, the vibration accelerations of the failure teeth are a little larger and manifest an increasing tendency with the growth of pitting area. The gear condition of severe failure can be diagnosed according to the original signal. However, it is difficult to diagnose the gear condition of slight failure only based on the waveform.

3. In the frequency spectrum of various gear conditions, the amplitudes of high-order harmonics and the natural frequency become larger with the increase of damaged area. Moreover, the sidebands also become stronger and broader. The frequency spectrum can represent particular characteristics of different gear conditions. Representative failure features can be extracted from the spectrum.

4. Comparing with the original signal, the method of residual signal can emphasize the abnormal amplitude generated by the gear damage. The evidence of fault impulse is a little more obvious in residual signals on gear box. Although the residual signal can strengthen the failure features of gear damage to some extent, it is still hard to diagnose the early gear faults only based on the residual signal.

5. The noise can be effectively reduced from the residual signal by employing the method of discrete wavelet transform. The processed signal is acquired by reconstructing the coefficients of discrete wavelet transform. In the processed signals of spot damaged gear and pitted gear, the difference of amplitude value is enlarged. Therefore, the fault indications are more clearly visualized in processed signals. It is confirmed that the method of discrete wavelet transform can contribute to strengthen the characteristics of gear damage.

6. Statistical parameters of standard deviation, root mean square value, kurtosis and skewness are extracted from the processed signal. The value of statistical parameters becomes larger along with the increase of the gear rotation speed and damaged area. Especially, the value of statistical parameters of normal gear is the smallest and changes slightly with the variation of gear rotation speeds. While, the parameters' value of spot damaged gear and pitted gear varies obviously with the variation of gear rotation speeds. The difference of parameters value between different kinds of gears is little when the damaged area is small.

7. The amplitude ratios of frequency bands approximately represent the characteristics of frequency spectrum and change with the variation of gear conditions. The amplitude ratio of the first frequency band becomes smaller with the increase of damaged area, while the amplitude ratios of the higher order frequency bands become larger. The statistical parameters and characteristic amplitude ratios of frequency bands can be adopted to demonstrate features of gear conditions.

8. The method of principal component analysis can transform the extracted failure feature vector into a fewer-dimensional inputting vector for classifiers of support vector machines. The distribution of samples in feature space can be generally illustrated based on the first three principal components. The data distribution of normal gear and slight failure gear with small damaged area is a little closer. The samples of severe failure gear or pitted gear are clearly separate with the other samples.

9. By using the method of support vector machines, most of the samples in damage contrast test are correctly classified into three types, called normal gear, spot damaged gear and pitted gear. The diagnostic accuracy of damage contrast test is 92.5%. The diagnostic accuracy of test data in cyclic test is 73%. The proposed method can correctly classify almost all the samples of normal condition and damaged condition. The capability of the proposed method in diagnosing the degree of damage is still need to be improved. By the technique of empirical mode decomposition, the

original signal can be decomposed into a number of intrinsic mode functions, each of which represents the local characteristics of the original signal and changes along with the variation of gear conditions. Therefore, the characteristic energy ratios can be extracted from the intrinsic mode functions as failure features to be input to the support vector machine classifiers. The diagnostic accuracy of test data in cyclic fatigue test is 82%. It is confirmed that the empirical mode decomposition method is effective for gear damage diagnosis and classification, even can improve the accuracy of diagnosis.