MONITORING OF THE GEAR WEAR OF A WIND TURBINE GEARBOX IN A TRANSIENT OPERATION

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During the wind turbine operation, the random variation of wind speed causes a fluctuated operation of wind turbine. In such a harsh transient operation condition, the gears transmitting the rotational energy will experience a severe load change and the gear life will be quickly shortened. In this work, it is intended to diagnose the level of gear teeth wear of a wind turbine gearbox in a transient operation. Two indicators are suggested to quantify the wear amount. First, the percentage of exceeding alarm level is used to quantify how many times the vibration amplitudes for varying RPM exceed 99.5% confidence interval of the healthy condition to indicate the existence of wear. Second, the maximum overshoot value of mean energy-difference is used to indicate the severity of wear condition. To calculate these indicators, one needs to identify the magnitudes of harmonics of gear meshing frequency. However, such harmonics are also time-varying, so an appropriate order tracking algorithm should be adopted to trace the harmonic components adapting to a transient speed variation. To this end, the STFT using the variable frequency resolution technique is employed. For the validation purpose, a gearbox with 1:90 speed ratio is tested. To compare the normal and wear conditions, the statistical distribution in normal condition is measured first. Among various probability distribution functions describing the vibration history, it is concluded from the chi-square goodness of fit test that the chi-square distribution is best fitted to the variation. The percentage of exceeding alarm level and maximum overshoot value of mean energy-difference are calculated as 38% and 25 dB at wear condition, respectively; while 0% and 10 dB at normal condition. From such big difference in indicator values, a clearly decision is made that the gear teeth are in severe wear condition.

1. Introduction

The wind turbine gearbox fluctuates randomly in operation due to the wind speed variation, the gear teeth life will be shortened by the load variation. Because the gear teeth contact periodically with the driven gear to transfer the rotational energy, the time-varying vibration of the gearbox
appears as the spectral harmonics of the gear mesh frequency (GMF) of the drive shaft. Thus, one can diagnose the gear condition by monitoring the harmonic amplitudes of the gear mesh frequencies. Conventional methods dealing with stationary condition are not suitable for the wind turbine gearbox in transient condition. In this work, a monitoring method which would be proper for diagnosing the gear wear condition in transient operation is suggested. To diagnose the gear condition, the order amplitudes of GMF in healthy condition is first traced from time-varying vibration signal to obtain the statistical distribution. The order amplitudes in RPM domain are analyzed by introducing an order tracking algorithm using the short time Fourier transform using variable frequency resolution (VFR-STFT), which was developed for the sound quality analysis, while the chi-square ($\chi^2$) goodness of fit test is employed for the assurance of the appropriateness of the statistical model. For the judgement of the gear health condition, two condition indicators are also suggested.

2. Suggestion of condition indicators for wear monitoring

Condition indicators are used to quantify or identify the fault condition. Conventional techniques monitor the change of statistical parameters such as skewness and kurtosis to diagnose the gear fault. However, those indicators are not proper for the wind turbine gearbox operating in transient condition.

To diagnose the wear of a gear in transient condition, two condition indicators are suggested by comparing the change of the order amplitude of GMF, which is traced by using an order tracking method. First, the Percentage of Exceeding Alarm level (PEA) is suggested to check the number of times in which the order amplitudes exceed 99.5% confidence interval in healthy condition. 99.5% confidence interval means that the possibility that the signal is in healthy condition is 99.5%. Because this confidence interval is related to the type I error, this error can be reduced by setting the significant level as 0.05. The PEA is defined as

$$PEA[\%] = \frac{N_{\text{exceed}}}{N_{\text{RPM}}} \times 100,$$

where $N_{\text{exceed}}$ denotes the number of RPM range exceeding 99.5% confidence interval in healthy condition, $N_{\text{RPM}}$ is the total number of RPM range.

Second, the Maximum Overshoot value of Mean Energy-difference (MOME) is also suggested to diagnose the gear fault. With the progress of the gear wear, the order amplitude of the GMF increases. Monitoring the maximum value of difference level between the monitored and the standard mean signal, one can quantify the severity of wear condition. This indicator is MOME, and it is written as

$$MOME[\%] = \max(L_{\text{RPM}}),$$

$$L_{\text{RPM}} = 10 \log_{10} \left( \frac{A_{M,\text{RPM}}}{A_{S,\text{RPM}}} \right)^2,$$

where $L_{\text{RPM}}$ represents the mean-difference level at each RPM, $A_{M,\text{RPM}}$ and $A_{S,\text{RPM}}$ the monitored and standard mean signal at each RPM respectively. Because the energy difference between monitored and standard mean signal can be obtained by using this indicator, the severity of wear condition is more quantitatively calculated.
3. Application: 5 kW wind turbine gearbox simulator

A test in the wind turbine simulator is conducted, which is a device virtually replicating actual wind environment. The wind turbine simulator consists of an operation part, a gearbox part, and a generator part. In this study, the wear condition of the 2nd planetary gear in the 5 kW wind turbine gearbox simulator works on fault diagnosis, and the gear wear is generated by driving gearbox at about 5243 RPM during the 16 hours. This simulator gearbox has a 1:90 speed ratio, and the configurations of wind turbine gearbox simulator are displayed in Fig. 1.

The measurement position of accelerometer (PCB, 352C33) in gearbox is near the 2nd planetary gear in horizontal axis. RPM and torque are measured by an encoder sensor (Ono Sokki, MP981) and a torque sensor (SETech, YDR) at the high speed shaft to measure the variations of the rotating speed.

This simulator was operated at the virtual wind speed, which is determined from the empirical wind model\textsuperscript{7}. Experiment is conducted 10 times to set the statistical distribution in healthy condition and 2 times to diagnose a wear condition. Figure 2 shows operation conditions of the simulator for 60 seconds.

![Measurement setup for a 5 kW wind turbine gearbox simulator](image1)

**Figure 1.** Measurement setup for a 5 kW wind turbine gearbox simulator.

![Operation conditions for the 5 kW wind turbine gearbox simulator](image2)

**Figure 2.** Operation conditions for the 5 kW wind turbine gearbox simulator: (a) simulated wind speed, (b) measured RPM, (c) measured power.

3.1 Identification of order amplitude of GMF using order tracking

Because the generated vibration energy of the 2nd planetary gear appears at the harmonics of the 2nd planetary GMF, the order amplitude of GMF should be monitored to diagnose the gear condition. To get a fine time and frequency resolution, this work uses an order tracking algorithm using VFR-STFT method, which was suggested in sound quality analysis\textsuperscript{3,4}. This method is similar with STFT algorithm and can obtain the fine frequency resolution at fixed time resolution by employing the algorithms for down sampling and linear interpolation. Considering the GMF change rate as 0.74 Hz during 0.01 s, the time and frequency resolution are determined as 0.01 s and about 1.0 Hz respectively. Table 1 shows signal condition for VFR-STFT method.
After obtaining the time-frequency map of vibration signal in gearbox, the harmonics of the 2nd planetary GMF are extracted by using the measured RPM signal, which is simultaneously measured with vibration signal. In this work, the 3 cases are considered to diagnose the gear fault; the first case is for setting a standard in healthy condition by conducting the experiment for 10 times, the second and the third cases are for monitoring a signal in healthy and wear condition by conducting the 2 times test. Each test condition is shown as Fig. 2.

Figure 3 represents the time-frequency map at each case. Using this time-frequency map and measured RPM signal, one can trace the order amplitude of the 2nd planetary GMF in transient condition. According to GL guidelines, the number of harmonics to diagnose the gear fault is suggested at least 1-4 harmonics. In this work, the first four orders of the 2nd planetary GMF are considered to monitor the fault condition. Figure 4 depicts RPM based order tracking results of the 2nd order of the 2nd planetary GMF at each case. Because the RPM based order tracking results has statistical characteristics, the statistical distribution should be set to make a standard of healthy gear condition. Here, a solid line is the mean signals at each RPM, and a dash line means 99.5% confidence interval, which is determined by using a selected distribution in healthy condition.

| Table 1. Signal processing conditions for the order tracking using VFR-STFT. |
|--------------------------|----------------|
| Sampling frequency (kHz) | 25.6          |
| Overlap / Window         | 75 % / Flat-top |
| Number of FFT            | 1024          |
| Down sampling steps      | 4             |
| Time resolution (s)      | 0.01          |
| Frequency resolution (Hz)| 1.56          |

![Figure 3. Time-frequency maps obtained by the VFR-STFT method: (a) a standard signal (healthy condition), (b) a monitoring signal in healthy condition, (c) a monitoring signal in wear condition.](image)

![Figure 4. Order tracking results in RPM domain at the 2nd order of the 2nd planetary GMF: mean; 99.5% confidence interval: (a) a standard in healthy condition, (b) a signal in healthy condition, (c) a signal in wear condition.](image)
3.2 Statistical distribution of the order amplitude in healthy condition

One can diagnose the gear fault by comparing a monitored signal with the standard signal. The statistical distribution is selected by comparing actual distribution, which consists of the observed order amplitude, and 99.5% confidence intervals in RPM domain are calculated by using selected distribution.

The chi-square goodness of fit test can find the best distribution function from the observed order amplitude. This goodness of fit test can be written as

$$\chi^2 = \sum_{i=1}^{n} \frac{(F_i - f_i)^2}{F_i}, \quad F_i = NP_i,$$

where $\chi^2$ denotes the chi-square value consisting of the observed frequency $F_i$ and the expected frequency $f_i$, $n$ is the total number of bines, $F_i$ the observed frequency representing the total number of the order amplitude $N$ and expected probability density function $P_i$. To test the suitability of statistical distribution, hypotheses should be checked. If $\chi^2$ is smaller than $\chi^2_{(n-1); \alpha}$, hypothesis is rejected. On the other hand, if $\chi^2$ is larger than $\chi^2_{(n-1); \alpha}$, hypothesis is accepted. Because the order amplitude of GMF are always positive, chi-square and Rayleigh distributions for one-sided test are compared with an actual distribution as displayed in Fig. 5. At the 2nd order amplitude at 11.5 RPM, the total number of bines $n$ is 20, and the total number of the order amplitude $N$ is 1456. Table 2 represents the results of the chi-square goodness of fit test at significance level $\alpha = 0.5$. Among 4 distributions, a chi-square distribution of 2 degree of freedom (DOF) is accepted, which has smaller $\chi^2$ than $\chi^2_{19;0.05}$.

To reduce the type I error, a significance level for a confidence interval is set as 0.05, so 99.5% confidence intervals in RPM domain are displayed in Fig. 4(a).

![Figure 5](image)

**Figure 5.** Selection the statistical distribution by using $\chi^2$ goodness of fit test (the 2nd order amplitude at 11.5 RPM) ; ■, actual distribution; - - - - $\chi^2$ of 1 DOF; - - - - $\chi^2$ of 2 DOF; - - - - $\chi^2$ of 3 DOF; - - - - Rayleigh.

<table>
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<th>Distribution</th>
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**Table 2.** The results of $\chi^2$ goodness of fit test ($\alpha = 0.5$).
3.3 Monitoring of the gear condition by using the suggested condition indicators

Exceeding Alarm level (PEA) and the Maximum Overshoot value of Mean Energy-difference (MOME) are suggested as the condition indicators to diagnose the wear of planetary gear. Figure 6(a) shows PEA results at each harmonic in healthy and wear gear condition. One can observe that the all value of PEA in healthy condition is 0%. On the other hand, PEA value of each harmonic is larger than 0%, and PEA of the 1st and the 2nd order much higher than that of the 3rd and the 4th order. Because this indicator can check whether or not the gear fault exists, it is difficult to diagnose other fault. The MOME values at each harmonic are calculated and shown in Fig. 6(b). The solid line is 99.5% confidence intervals at each order. Among the 4 harmonics, the maximum values of MOME in healthy and wear condition are 10 dB and 25 dB respectively. MOME value of healthy gear is smaller than 99.5% confidence interval, but that of the wear of a gear larger than 99.5% confidence interval. Because the vibration level increases when the wear fault progress, other fault conditions can be diagnosed by using MOME indicator.

![Figure 6](image)

Figure 6. Condition monitoring at a planetary gear; monitoring a mean signal in healthy condition; monitoring a mean signal in wear condition; _99.5% confidence interval: (a) percentage of exceeding alarm levels, (b) maximum overshoot value of mean energy-difference.

4. Conclusions

Generated vibration signal at the wind turbine gearbox is in the transient condition due to its random operation. To diagnose the gear fault of wind turbine gearbox, a proper fault diagnosis method in transient condition is required. This work diagnoses the wear of 5 kW wind turbine gearbox simulator, and experiment is repeatedly conducted to set the standard for healthy condition, and 2 times to monitor the gear in healthy and wear condition.

According to experiment in healthy condition, the statistical distribution is selected by using the chi-square goodness of fit test. Among the variable distribution functions in this signal condition, a chi-square distribution of 5 DOF is the best fit, and 99.5% confidence intervals in RPM domain is determined by using this selected distribution function. The experiment in healthy and wear condition are conducted 2 times to compare the monitored and standard mean signal. Because the monitored mean signal in healthy condition is in the 99.5% confidence interval, all values of Percentage of Exceeding Alarm level and the maximum value of Maximum Overshoot value of Mean Energy-difference are 0% and 10 dB respectively. In the case of wear condition, all values of Percentage of Exceeding Alarm level are larger than 0% and the maximum value of Maximum Overshoot value of Mean Energy-difference is 38 dB. The existence of wear can be indicated by analyzing the Percentage of Exceeding Alarm level. However, this indicator can only be able to check the existence of the wear. It is difficult to quantify the severity of wear condition. To solve this problem, Maximum Overshoot value of Mean Energy-difference is suggested to define that how much difference be-
between the monitored and standard mean signal are. The severity of wear condition can be quantified by using this indicator.

Acknowledgments

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REFERENCES