Mechanical Systems and Signal Processing 108 (2018) 262–275

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Gear fault diagnosis using transmission error and ensemble empirical mode decomposition

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ARTICLE INFO

Article history:
Received 27 April 2017
Received in revised form 21 January 2018
Accepted 14 February 2018

Keywords:
Gear fault
Transmission error
Gear spall
Gear crack
Diagnostics
Ensemble empirical mode decomposition
Fault classification

ABSTRACT

Classification of spall and crack faults of gear teeth is studied by applying the ensemble empirical mode decomposition (EEMD) to the transmission error (TE) measured by the encoders of the input and output shafts. Finite element models of the gears with the two faults are built, and TE's are obtained by simulation of the faulty gears under loaded contact to identify the different characteristics. A simple test bed for a pair of spur gears is prepared to illustrate the approach, in which the TE's are measured for the gears with seeded spall and crack, respectively. EEMD is applied to extract fault features under the noise from the measured TE. The differences of the spall and crack are clearly identified by the selected features of the intrinsic mode functions based on the class separability criterion. The k-nearest neighbor method is applied for the classification of the faults and normal gears using the features. The proposed method is advantageous over the existing practices in the sense that the TE signal measures the gear faults more directly with less noise, enabling successful diagnosis.

1. Introduction

For more than decades, great deal of research have been devoted to fault diagnostics of critical components in rotating machineries to achieve increased reliability of the system while reducing the operating cost. Among these, gearbox undergoing extreme loading conditions as used in helicopters and wind turbines has been the primary subject of intensive investigation. Typically, there are two types of gear faults leading to failure: one is the spall that chips off the surface of the teeth and the other is the crack formed at the root of tooth due to the repeated bending stress. Usually, crack is regarded as more critical since it grows suddenly to the tooth breakage, resulting in the whole system loss. This is why not only the faults detection but also their classification is important in the diagnostics.

The diagnosis of gear fault has been mainly approached by the vibration sensors because of the ease of installation and cost efficiency. The related techniques are well established over the long periods of development. Numerous reviews are found in the literature with this topic; see, for example [1,2]. The vibration based technique, however, has its limitation that it is weak against the background noise and mechanical resonance, which usually exist in practice. In order to overcome

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https://doi.org/10.1016/j.ymssp.2018.02.028

these, studies using acoustic emission (AE) sensors have grown over the recent years since the AE mainly detects high frequency elastic waves, which is less affected by the noise and resonance (see [3–6]). This method however has drawbacks due to the cost for higher sampling rate and requirement for the sensors to be close to the source to avoid unwanted attenuation.

Recently, transmission error (TE) has received another attention as an alternative way for the gear fault diagnosis. TE is defined as the angular difference between the ideal and actual position of the output gear, which results from the finite stiffness of the meshing gears and the manufacturing errors. TE is obtained by optical encoders attached to the input and output shafts that measure the rotational speed to very high accuracy. Considering the measurement ability with less disturbances, the TE based technique may offer more accurate diagnostics than those of the traditional ones. Li et al. [7] estimated crack size of tooth by employing the FEM to compute tooth stiffness, applied lumped parameters model to simulate the gear dynamic behavior, and obtained the TE over a cycle. Feki et al. [8] did the similar study for the TE's with different loading levels by the simulation of dynamic model. While they have experimented to measure the TE, it was only to compare the raw signal with the simulation in an elementary manner, which is hard to speak of the diagnosis. Endo et al. [9,10] have made FEA simulations of the spall and cracked tooth to study the TE behavior and found that the effect of tooth cracks is load dependent, while the effect of spalls is geometry dependent. After examining the shapes of residual TEs and their derivatives by the FEA, however, they have used vibration signals in practice to classify the spall and crack, which is not the TE based technique. Park et al. [11] have proposed to use the peak to peak (P2P) TE as the feature based on the observations in the experiments that the P2P TE becomes pronounced under the fault conditions. As already mentioned, all of these studies on the TE have lacked the steps for the rigorous signal processing and feature extraction that is essential for the practical diagnosis. More recently, Fedala et al. [12,13] have carried out fault classification of gears using the classical time and frequency domain features obtained from the TE and acceleration signals. They have concluded that the TE shows superior performance over the acceleration signals.

In this study, ensemble empirical mode decomposition (EEMD) technique [14] is proposed to extract features useful for the detection and classification of the gear faults: spall and crack. The EMD has recently emerged as a new time-frequency analysis technique suitable for nonlinear and non-stationary signals occurring in the faulted rotating machineries. Many publications on the use of EMD are available for gears (see [15]). Followed by the early applications of original EMD such as the paper by Loutridis [16], several papers have followed to improve the EMD. More lately, ensemble EMD, which is the most representative version of improved EMD was developed by Wu and Huang [14] by adding noise to the investigated signal. Since Ai and Li [17] has applied the EEMD to the diagnosis of gear crack and demonstrated the effectiveness by experiments, several studies have followed for more enhancement or application to the more complex cases [18–20]. However, all of the EMD studies have been based on the vibration signals, and none of the prior work has studied the TE signal as applied to the EEMD in the gear fault diagnosis.

In this study, the EEMD, which was found feasible in the vibration based diagnosis, is applied to the TE signal for a single stage spur gears in motion. The objective is to develop an effective method that distinguishes the two faults: spall and crack from the normal ones in a systematic way. To achieve this goal, FEAs are first conducted to figure out the different behaviors of tooth deformation for normal and faulty gears in meshing. Virtual TE signals are then generated to simulate the gears in rotary motion by incorporating the low frequency waves. EEMD is applied to the residual TE (RTE) which is the difference between the faulty and normal signal, to obtain a set of intrinsic mode functions (IMF). The distinct behaviors of the spall and crack are easily identified from the resulting IMF simulations. A simple test bed is installed to illustrate the approach for a single stage gear system. TE's are measured from the three states: normal, spalled and cracked gears, respectively. The profiles of residual signals of measured and simulated TE's are in good agreement, thus suggesting a useful role of FEA model in the diagnostic process. This may be due to the use of encoders for the measurement, which is less affected by the intervening disturbance or noise. EEMD is applied to the real RTE to obtain the IMF's, from which the features are selected and classification is performed using the k-nearest neighbor technique. The advantage of this approach is that the FEA enables the identification of the types of the fault in the EEMD process of the TE signal, which is not tractable by the other methods such as vibration or acoustic emission signals. This was already noticed by Endo et al. [9,10], although they did not continue to the diagnosis study with TE signals.

2. Overall procedure of the proposed method

The overall procedure of the proposed method is displayed in Fig. 1, which consists of the steps: (1) TE data are acquired from the FEA as a virtual signal or from the test bed as a real signal; (2) the signals are preprocessed to obtain residual TE by removing unnecessary noise and frequency components; (3) EEMD is applied to decompose the signal into a set of IMFs which allows more chance to find fault information; (4) time based features are extracted from each IMF and best two features are selected that shows largest separability performance; (5) faults are classified using the chosen features data based on the classification algorithm. In Section 3, the procedure using simulated signal is explained, which explores the feasibility of TE signal for the fault diagnosis. In Section 4, the procedure is implemented using the real data from the test bed to obtain the classifier that can diagnose the faults. Conclusions are outlined in Section 4.