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Compound gear-bearing fault feature extraction using statistical features based on time-frequency method

Laxmikant S. Dhamande[a,*], Mangesh B. Chaudhari[b]

[a] Department of Mechanical Engineering, Sanjivani College of Engineering, Kopargaon, 423603 (SPPU, Pune), India
[b] Department of Mechanical Engineering, Vishwakarma Institute of Technology, Bibwewadi, Pune 411037, India

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ABSTRACT

A small incipient fault in gear and bearing causes multiple faults in gear-bearing system leading to catastrophic failure. The purpose of present study is to explore more complex situation of compound gear-bearing fault. The compound faults such as a fault in the inner and outer race of bearing along with two teeth of gear having corner damage or three teeth of gear having corner damage, etc. are investigated using experimentation. To improve the effectiveness of diagnosis, vibration measurement is done at different speed and load condition. This paper proposes new compound fault features, extracted from continuous and discrete wavelet transform of vibration signal. The methodology consist of proposing the features in time–frequency domain and comparison of its diagnostic potential with respect to the features extracted from time and frequency domain for compound fault identification using three different classifiers. The fault classification accuracy of these features is found to be better than the conventional time and frequency domain parameters.

1. Introduction

Gears and bearings are the most important and critical machine components in condition monitoring of rotating machineries like gear boxes of all automobiles, machine tools, aircrafts, turbines, etc. The failure of gears or bearings is one of the most frequent reasons for machine breakdown. Number of mechanical system wear out failures are due to bearings and shock loading and pitting failures of gears. Therefore the detection of faults in gears and bearings is the important task for maintenance engineer using condition based maintenance to avoid catastrophic failure. The existing work in this area is concentrated on either gear or bearing fault diagnosis. It is observed that a good amount of work has been carried out by number of researchers on development of different techniques such as wavelet transform [1–4], envelop analysis [5], empirical mode decomposition method [6,7] for identification of single and multiple faults in bearings. Similarly the techniques such as time-frequency distribution [8,9], wavelet transform [10,11], statistical feature extraction [12–16], multi-scale morphological filters [17] are satisfactorily applied for gear fault identification. In addition to this multiple fault identification is carried out using methods such as adaptive spectral kurtosis [18], spectrogram [19], and time-frequency methods [20–25]. However, it is possible that the fault may be present in both gear and bearing leading to compound fault in transmission system [26–35] which needs effective diagnosis system. The main intention of these techniques is to minimize the time and cost of machine repairs, or its effective implementation. It is found that these techniques are very lengthy and needs an expert in the field for making decision. So it is needed to give a solution to this problem by providing a methodology which is easy to understand and also possible to apply effectively and automatically. In this work a methodology is proposed for identification of compound fault using statistical features. If there is a fault in bearing it will affect the gear vibration signature and vice versa [27]. The analysis of individual bearing or gear fault by the diagnosis system may generate erroneous results. In actual practice, there may be faults in both gear and bearing, so it is required to extract the statistical features from vibration signal which can detect the multiple compound faults.

Various techniques have been studied by researchers for detection of local and distributed faults in gear and bearing systems such as wear, pitting of gear teeth, spalls and tooth fillet crack in gear, worn and broken teeth, chipping, breakage of more than one tooth and complete removal of one tooth, inner and outer race fault in bearing, etc. using vibration signal. A more challenging task is to explore simultaneous multiple faults in both gear and bearing. In machinery fault detection basically two types of methodologies are used, visual inspection by qualified personnel and feature extraction and classification by using machine intelligence. Singh and Kumar [4] have shown how bearing groove race fault width can be measured using wavelet decomposition

* Corresponding author.
E-mail address: lsdhamande@rediffmail.com (L.S. Dhamande).

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of vibration signal. Wang et al. [11] investigated the sensitivity and robustness of techniques such as amplitude and phase demodulation, beta kurtosis and wavelet transform for healthy gears, filed, chipped, and cracked gears. It is found that the beta kurtosis is a very reliable time-domain diagnostic technique, while phase modulation is sensitive to imperfections in gears, and continuous wavelet transform provides a good visual inspection. A time and frequency domain vibration signal is generally used by the analyst for detecting faults in a system. Saravanan and Ramachandran [15] have analyzed the gear faults such as face wear and tooth breakage by extracting features using discrete wavelet transform and artificial neural network is used as a classifier. Bordoloi and Tiwari [20] have used features from frequency domain for single gear fault identification using support vector machine classifier. Sawalhi and Randall [26] have prepared a simulation model to understand the gear and bearing interactions. The comparison of inner and outer race fault in bearing is presented by using simulated model and experimental measurement by spectrum comparisons, Spectral Kurtosis (SK) analysis and envelope analysis techniques. Dhamande and Chaudhari [27] have used statistical features in time and frequency domain for detection of combined gear-bearing fault using artificial neural network. Any vibration signal collected contains noise, so for analyzing the signal different de-noising or filtration methods are used. Ibrahim et al. [28] have used the adaptive filtering technique with least mean square algorithm for extraction of gear box fault features i.e. gear mesh frequency and their sidebands. Gan et al. [30] have proposed a multi-domain manifold method for extracting features from faulty gear and bearing.

In the current work a novel thing is that, the more complex but real situation is considered where the compound multiple faults in gear and bearing i.e. multiple faults in multiple components are investigated, which is an uncovered field of research. This is a very critical situation which will cause the failure of the system quite early than the single or multiple incipient faults in individual component. Here an effort is made to extract useful features such as standard deviation, variance and absolute maximum from wavelet coefficient plot of Continuous Wavelet Transform (CWT) at scales corresponding to gear mesh frequency and its harmonics and from discrete wavelet transform of the measured vibration signal for compound fault identification.

2. Experimental data collection

2.1. Experimental set-up

The schematic of the experimental set up is as shown in Fig. 1(a). It consists of a rotor bearing system driven by a 0.5 HP, 3000 rpm D C motor. The rotor bearing system is a model of turbine. The power is transferred to a single stage spur gear box through belt and pulley arrangement. A gear box having 26 teeth on pinion and 46 teeth on gear with a module of 2.11 mm and 20 mm face width is provided with a dynamometer for applying load torque [27]. The bearing supporting gear box driving shaft is 6004 type of single row deep groove ball bearing. A single accelerometer having sensitivity 100 mV/g ($g = 9.81\ m/s^2$) is placed on the gearbox casing in the radial (vertical) direction over the faulty bearing. To get maximum diagnosis accuracy, measurements are carried out at the location close to the faulty gear, which is mounted on driving shaft and supported on faulty bearing. Vibration amplitude in terms of velocity is measured with the help of a four channel Fast Fourier Transform (FFT) analyser. The sampling frequency used is 16,384 Hz. Total six compound faulty conditions of gear and bearing are created. The fault on driver gear is created by removing a small amount of material from the corner of tooth indicating a triangular area of about $3\ mm^2$ by filing as shown in Fig. 2(a). The two faulty conditions of gears are corner of two teeth damaged and corner of three teeth damaged at 120^0 apart, while the third faulty condition on gear is created by removing one tooth completely. A local circular fault of 0.8 mm in size on the outer and inner race of the bearing is created by Electro Discharge Machining (EDM) as indicated in Fig. 2(b). The two faulty conditions on bearing are two holes on outer race and one hole on each inner and outer race of bearing. As a representative of these faults, two teeth of gear having corner fault and one fault (pit) on each inner and outer race of bearing are as shown in Fig. 2(a) and (b).

To analyze the effect of compound fault on vibration signal, measurements are done for seven different conditions of gearbox. The seven different conditions considered are as indicated in Table 1. The effect of atmospheric conditions such as temperature, moisture is accounted by collecting vibration signals at regular interval of time. The experimental setup is properly tightened, aligned and balanced to avoid the peaks at shaft frequency (1X) and its harmonics, which may be introduced due to presence of mechanical faults such as unbalance (at 1X), misalignment (at 2X), and looseness (at 1X, 2X, 3X………etc.). The operating speed of 1000 rpm with variation of speed between 970 and 1030 rpm with a step size of 10 rpm is used. The loads are varied as 10 N, 20 N, 30 N, and 40 N respectively. The setup is run for some time and readings are collected after attaining the stable condition. Initially the readings are collected from healthy condition of gearbox. The pinion shaft is removed and a faulty pinion with two teeth having corner fault is mounted on it. The pinion shaft was initially supported on healthy bearing, which is then replaced by a faulty bearing with two faults on its outer race. The vibration signals are then measured from a first compound fault condition where there are two faults on outer race of bearing and two teeth of gear having corner damage. Similarly other compound fault conditions are created in experimental setup and vibration signals are measured from it. In the present study, results from a test conducted on a healthy gear and bearing is presented and discussed along with the faulty gear and bearing. A healthy gear vibration signal contains several gear meshing harmonics with a few accompanying sidebands but, of low amplitude. Here, the shaft speed is 1000 rpm i.e. 16.67 Hz, and gear mesh frequency is 433.42 Hz. The effect of each type of fault on the vibration signal is different; hence it is possible to extract the features from vibration signal which can detect the fault more precisely.

2.2. Methodology and procedure

The methodology followed in this work (Fig. 3) consists of use of an experimental setup where it is possible to introduce the multiple faults in gear and bearing simultaneously. The different components used in this setup such as bearing block, bearing, shaft, gear, input and output pulleys are connected to each other, so the vibration due to gear interaction is transferred from gears to shaft, shaft to bearings and from bearings to bearing block or housing. This connectivity makes the vibration signal measured by accelerometer at housing surface a complex multi-component signal. This signal is generated by shaft rotation, tooth meshing, bearing vibration, gearbox resonance vibration and noise due to interaction of all the components. The actual measured vibration signal is a mixed signal of gear and bearing, hence a novel thing is, to detect more complex and real situation in transmission machinery where multiple components have multiple faults in it. The time and frequency domain signal measured using an accelerometer in terms of velocity is used for analysis. For identifying the compound fault in the gear box system, raw vibration signals are measured from a single stage spur gear box in seven different conditions. In each faulty condition minimum three and maximum five faults are present on gear and bearing in combination.

The methodology followed in this work consists of following important steps:

1. It consists of preparing an experimental set-up where compound multiple faults in gear and bearing can be introduced.
2. Measuring time and frequency response of vibration along with the overall Root Mean Square (RMS) and range of amplitude using FFT analyser. A single accelerometer is located at the top of gear box