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Statistical modeling of gear vibration signals and its application to detecting and diagnosing gear faults

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ABSTRACT

A statistical model of gear mesh vibration signals is proposed in this paper. It is seen that the sample mean is first removed from the gear mesh vibration signal, and the remaining signal components are approximated with a set of sinusoidal functions in the signal model. The signal model parameters can be estimated by the least-square method and the optimal model order is determined based on the Akaike Information Criterion (AIC) or the modified Bayesian Information Criterion (BIC). Within the framework of the signal model, to perform the gear fault diagnosis and analysis, the residual signal between the synchronous signal average and the output of the optimal signal model is further computed and the corresponding kurtosis values are employed for efficiently detecting the gear tooth fault.

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1. Introduction

It is well known that vibration analysis is an effective approach for analyzing, detecting and diagnosing gear faults in industrial systems [1–3,6,7,11,12]. However, because the measured vibration signals are often disturbed by uncertain impulses and random noises, it is essential to employ some signal processing techniques in the fault diagnosis algorithms to attenuate the effects of disturbances and ensure that more accurate gear fault features can be extracted. In most of gear fault diagnosis systems, the synchronous signal averaging (SSA) technique [6,8,11,12] is often used first to filter away high frequency disturbances from the measurements, and the signal average of gearbox vibration signal, which contains the main components of the vibration signals of the gear of interest, is then further processed for the purpose of fault detection and diagnosis.

The residual signal analysis on SSA has received a great deal of attention, as one of the most popular techniques for gear fault diagnosis in the past two decades [6,8,11,12]. It is known that, for a healthy gear, its SSA is dominated by gear meshing harmonics and low-order amplitude and phase modulation components. However, when a local gear crack occurs, some higher shaft-order modulation sidebands with lower amplitudes will be produced, and structural resonances may then be excited. The removal of regular meshing harmonics and their low-order sidebands from the SSA results in the classical residual signals. Some statistical measures of residual signals can be applied to quantify fault-induced abrupt changes. These statistical measures include variance, kurtosis, quasi-normalized kurtosis and some ratios [2,11].

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Another important approach for extracting the gear fault information from the SSA is called the narrow demodulation technique. The key point of this technique is to utilize a band-pass filter to extract the demodulated signal components with the features induced by the gear crack. If the bandwidth of filter can be properly chosen, the extracted demodulated signals can provide sufficient gear fault information for diagnosis [2,4,7]. It should be noted that the selection of bandwidth is a very important factor that influences the effectiveness of the narrow demodulation technique for gear fault detection and diagnosis.

Among many of time–frequency analysis techniques on SSA or residual signals, the spectrogram (the squared modulus of short-time Fourier transform – STFT) and Wigner–Ville distribution (WVD) are often used for gear fault diagnosis [10,11]. For non-stationary signals, continuous wavelet transform is regarded as an effective tool for characterizing signals at different levels and detecting sudden changes and transients in gear signals [15].

In this paper, a statistical model of describing the gear mesh vibration signals is developed. The proposed model is divided into two parts: the deterministic part is expressed as the sum of a set of sinusoidal functions, while the random part is a white noise term. The model order is optimized with Akaike's Information Criterion (AIC) and modified Bayesian Information Criterion (BIC), respectively. The model parameters can then be estimated by using the least-square method. It is found from this research that the optimal model order determined by BIC are smaller than the one determined by AIC. However, the different optimal model orders do not have a significant influence on fitting the same SSA. With all estimated values of the signal model for each group of SSA data, the residual signal data can then be generated by subtracting the outputs of the optimal signal model from the original SSA data. Our computational results show that the kurtosis of residual signal data can be used to efficiently diagnose the gear crack occurrence. In comparison to other parametric models, such as AR models and ARMA models, the statistical signal model proposed in this paper has distinct advantages in fitting all of gear signal data, and the corresponding model-based technique is extremely effective for diagnosing gear faults.

This paper is organized as follows. In Section 2, a gear test rig as the platform of this research is briefly described. In Section 3, the new statistical model of the gear mesh vibration signals is developed, and both the model parameter estimation with the least-square method and the optimal determination of the model order based on AIC and BIC are discussed in detail. In Section 4, a set of (G6) gear tooth crack propagation test data is used to confirm the effectiveness of the developed scheme with the excellent performance. Finally, conclusions are given in Section 5.

2. Gear rig tests

The experiments of gear vibration were conducted [12] for investigating tooth crack growth in spur gears. The test rig was run under a fixed input shaft speed of 2400 rpm (40 Hz) and a variable load from 0 kW to 45 kW with the configuration shown in Fig. 1. The test gearbox is driven by an electric motor through a belt drive, which supplies a full loading capacity

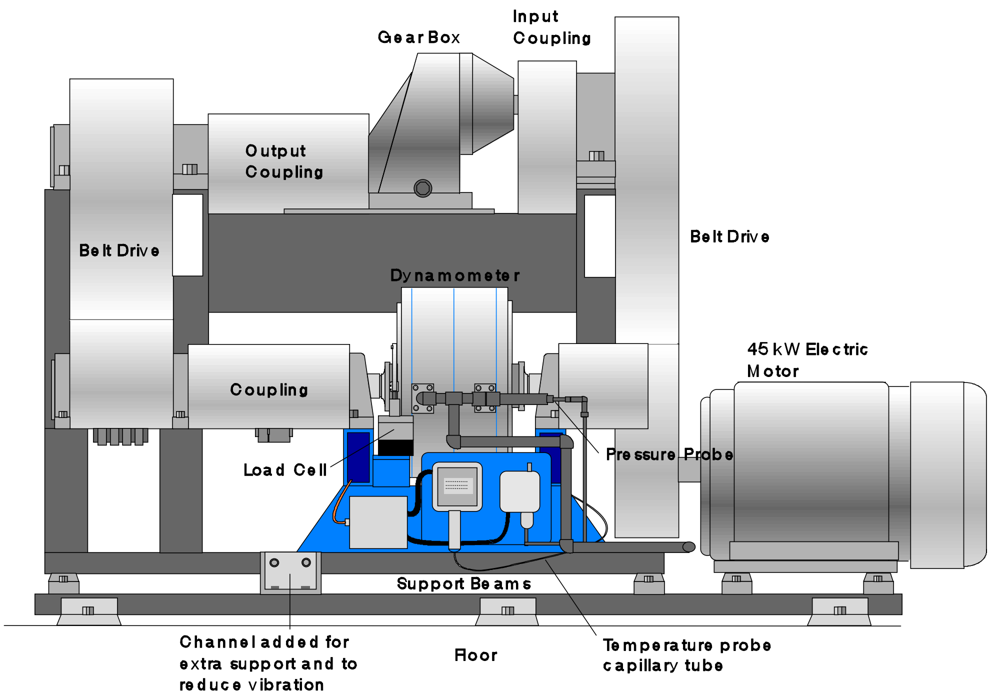

Fig. 1. The DSTO gear test rig.

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