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A novel approach integrating dimensional analysis and neural networks for the detection of localized faults in roller bearings

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ABSTRACT

The detection of the defective/worn out bearing components used in rotating machines is one of the main concerns in various applications. To improve the computational efficiency in the nonlinear dynamic analysis for the rolling contact bearings, a new methodology based on dimensional analysis (DA) theory is proposed in this paper. The developed model is used to predict the vibration responses due to artificially spalled bearing components to quantify the level of structural damages into these components. The use of a back propagation neural network (BPNN) has been made that also predicted responses from the network trained by developed algorithm using the experimental data obtained from the defective bearing components on the developed test rig. A comparison between the responses predicted by proposed DA method and the BPNN showed a fair amount of the agreement between the two approaches and validated the proposed model and proved outstanding tool for identification of spalled/damaged bearing components.

1. Introduction

The main causes of breakdown of rotating machines are the faults in the rolling element bearing. Hence, to avoid such kinds of premature failures, many techniques for health monitoring of the bearings have been developed. Out of these techniques, vibration based fault analysis proven to be more advantageous in revealing bearing failure. Wang and Kootsookos [1] established general model of faulty rolling element bearing vibration signals and compared simulated data with the experimental data and showed the usefulness of proposed method based on envelope-autocorrelation for fault detection of low shaft speed bearings. Vibration signature analyzing schemes such as frequency domain analysis and chaotic vibration analysis (modified Poincare diagrams) are applied and their effectiveness in pinpoint damage are compared in this study [2] and extent of the damages agreed with the vibration amplitudes.

The rotor-bearing system has been modeled as a three degrees-of-freedom system and predicted significant components at the harmonics of characteristic defect frequency for a defect on the particular bearing element [3]. Samanta et al. [4] compared the performance of three types of artificial neural network (ANN), namely, multilayer perceptron (MLP), radial basis function (RBF) network and probabilistic neural network (PNN), for bearing fault detection and showed that with integration of the GA with MLP and GA with PNN, fault detection rates are very high. This paper [5] proposed a new fault diagnosis procedure which integrated wavelet packets fractal techniques and RBF neural networks in that the main purpose was to investigate different fault conditions. Arslan and Aktürk [6] developed a nonlinear model considering the shaft bearing system as a spring-mass system that identified damages in angular contact ball bearings. Chun-Chieh et al. [7] proposed a method integrating the time series analysis based on autoregressive (AR) method and BPNN and showed that the difference value of AR coefficients with BPNN is more effective in the damage detection.

Huaqing and Peng [8] proposed an intelligent diagnosis method for detection of the bearing faults on the basis of possibility theory and a fuzzy neural network in that analysis was done on the vibration features extracted from frequency domain signal. Desavale et al. [9,10] formulated a mathematical model based on the conventional Buckingham's pi theorem and integrated the neural networks for fault diagnosis of the spherical roller bearings however, a clear distinction between the different defect conditions has not given in this paper. Dick et al. [11], put forth a method for calculating and analyzing the load distribution which is reported to be quasi-static and nonlinear stiffness of a radially loaded double row bearing with a raceway defect of varying depth, length, and

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Nomenclature

d	cone bore diameter (mm) [L]
D	cup outside diameter (mm) [L]
B	cone length (mm) [L]
d_1	pitch diameter (mm) [L]
d_r	rolling element diameter (mm) [L]
Z	no. of rollers [–]
m_i	mass of inner race (kg) [M]
m_o	mass of outer race (kg) [M]
m_s	mass of shaft/rotor (kg) [M]
m_r	mass of roller (kg) [M]
L	length of roller (mm) [L]
α	contact angle (°) [–]
E	Young's modulus (N/m^2) [F L^{-2}]
ρ	material density (kg/m^3) [F L^{-4} T^2]
K	constant for contact deformation (N/mm$^{1.11}$) [F L$^{-1.11}$]
δ	bearing deflection (mm) [L]
F_H	Hertzian contact force (N) [F]
C	damping coefficient (N s/m) [F L^{-1} T^1]
Δ	defect size (mm) [L]
n_d	no. of defects [–]
r_c	radial clearance (mm) [L]
N	speed of shaft (rpm) [T^{-1}]
W	radial load (N) [F]
F_a	axial load (N) [F]
M_u	unbalance (g) [F L^{-1} T^2]
ν	lubricant viscosity (mm^2/s) [L^2 T^{-1}]
$\ddot{x}, \ddot{y}$	vibration acceleration (m/s^2) [L T^{-2}]
f_{BPFO}	outer race defect frequency (Hz) [T^{-1}]
f_{FTF}	fundamental train frequency (Hz) [T^{-1}]
f_{BSF}	roller spin frequency (Hz) [T^{-1}]
f_{RDF}	roller defect frequency (Hz) [T^{-1}]

Abbreviations

DA	dimensional analysis
ANN	artificial neural network
RBF	radial basis function
AR	autoregressive
HE	hierarchical entropy
MMDA	matrix method of dimensional analysis
BPNN	back propagation neural network
MLP	multilayer perceptron
PNN	probabilistic neural network
SVM	support vector machines
MSE	multi scale entropy
NN	neural networks

surface roughness. The proposed method was then applied to ball bearings on gearbox and fan test rigs seeded with line or extended outer raceway defects. Rafsanjani et al. [12], developed mathematical expressions for inner race, outer race and rolling element with localized defects. In this model nonlinear Hertzian contact deformation and radial clearance was considered in the modeling the contact force. Jalan and Mohanty [13] developed model based technique based on residual generation. This technique makes use of experimental vibration data obtained from a rotor bearing system subjected to misalignment and unbalance and calculates the residual forces due presence of the faults and compares these forces with the theoretical forces due to the faults. Wensheng et al. [14], integrated Morlet wavelet filter and autocorrelation function to develop a method which works in two steps. In first, signal filtration is carried out to eliminate the noise related frequency components using Morlet wavelet based band-pass filter in that the wavelet parameters are optimized by making use of genetic algorithm. In second step, in order to clearly visualize the defect generated periodic impulsive feature, an auto correlation algorithm is applied on the previously filtered signal. Bubathi et al. [15], proposed a new technique based on singular spectrum analysis in which principal fault features related singular values were extracted from the bearing vibration signal and used to train the neural network for automated fault detection scheme. Fatima et al. [16], proposed an algorithm based on the support vector machines (SVM) for the classification of the faults in rolling contact bearings along with the presence of unbalance. They considered the time domain vibration data for the classification of the faults and experimentally found that the proposed method works well with fault classification rates as high as 75–100%. Jena and Panigrahi [17], presented a method for the measurement of the defect width in taper roller bearings based on the experimental investigation applying the signal processing techniques. A wavelet transform is used for the de-noising the original vibration signal before using the signal for further time-frequency analysis using continuous wavelet transform. A time interval between the entry and exit events of rolling over the defect is used as a factor that correlates the defect width. Sidra et al. [18], put forth a theoretical model for the forcing function developed on the structure due to the presence of the outer race defect. Use of contact mechanics was made to model the force impact due to the defect. A time impact between entry and exit events of the spall was used to roughly estimate the size of the spall and further extended this work to predict the spall sizes on the inner race [19]. Chen et al. [20], developed an intelligent fault diagnosis scheme based on the support vector machines (SVM). A particle swarm optimization algorithm was used to optimize the parameters of the fault classifier. They experimentally showed that the fault classification accuracy of the proposed method is more as compared to the traditional SVM classifiers. Zhu et al. [21], proposed a fault feature extraction method based on the hierarchical entropy (HE). A support vector machine (SVM) was trained using the extracted fault features obtained by HE using particle swarm optimization algorithm. They experimentally found that the fault detection accuracy of the proposed method is more as compared to the multi-scale entropy (MSE). Dong and Qiang [22], presented a Gaussian random walk based Bayesian method for the extraction of the fault related vibration features. The experimental and simulated results showed the potential of the method for the detection of the faults. Li et al. [23], applied finite element method for modeling the elastic deformation of the rotor. The dynamic model of the whole rotor-bearing system was proposed. Experiments were performed for validation of the proposed model and reported the significant increase of the vibration amplitudes with increase in the radial clearance. Liu et al. [24] proposed a new mathematical model considering new force-displacement relationship replacing the Hertzian relationship. Also, the relationship between the contact stiffness and the defect was given. The statistical parameters such as RMS value and the kurtosis were used as a response parameters that are affected by the impulse force generated by the presence of defect and increase with the defect size.

In addition to these Refs. [4,5] and [7–10], these Refs. [25,26] highlighted the implementation of the artificial intelligence technique to applications such as drilling. In particular, Panda and