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Comparison of dimensionality reduction techniques for the fault diagnosis of mono block centrifugal pump using vibration signals

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ABSTRACT

Bearing fault, Impeller fault, seal fault and cavitation are the main causes of breakdown in a mono block centrifugal pump and hence, the detection and diagnosis of these mechanical faults in a mono block centrifugal pump is very crucial for its reliable operation. Based on a continuous acquisition of signals with a data acquisition system, it is possible to classify the faults. This is achieved by the extraction of features from the measured data and employing data mining approaches to explore the structural information hidden in the signals acquired. In the present study, statistical features derived from the vibration data are used as the features. In order to increase the robustness of the classifier and to reduce the data processing load, dimensionality reduction is necessary. In this paper dimensionality reduction is performed using traditional dimensionality reduction techniques and nonlinear dimensionality reduction techniques. The effectiveness of each dimensionality reduction technique is also verified using visual analysis. The reduced feature set is then classified using a decision tree. The results obtained are compared with those generated by classifiers such as Naïve Bayes, Bayes Net and kNN. The effort is to bring out the better dimensionality reduction technique–classifier combination.

1. Introduction

Condition monitoring is used to find faults at an early stage [10] so that diagnosis and correction of those faults can be initiated before they become more prominent and lead to loss in productivity. Unexpected breakdown of mono block centrifugal pump parts increases the down time and maintenance costs. This has motivated academic researchers and industrial experts to focus their attention on such studies using the contemporary techniques and algorithms available in this field.

Bearings fault, impeller fault, seal fault and cavitation [13] can cause serious problems such as noise, high vibration, leakage etc. and degrade the performance of the mono block centrifugal pump [12]. In order to keep the pump performing [35] at its best, different methods of fault diagnosis have been developed and used effectively to detect the machine faults at an early stage. Vibration analysis is the one of the prime tools to detect and diagnose mono block centrifugal pump faults [11]. Vibration based pump condition monitoring and diagnosis involves data acquisition from the mono block centrifugal pump, feature extraction from the acquired data, feature selection, and interpreting the results.

Different methods and approaches are used for fault diagnosis. Rajakarunakaran et al. [21] proposed a model for the fault detection of centrifugal pumping system using feed forward network with back propagation algorithm and binary adaptive resonance network (ART1) for classification of seven categories of faults in the centrifugal pumping system. In the work reported by Sakthivel et al. [23]; the use of Support Vector Machines (SVMs) and Proximal Support Vector Machines (PSVMs) as a tool for accurately identifying and classifying pump faults was presented. SVM was found to have a slightly better classification capability than PSVM. Sakthivel et al. [24] presented the use of decision tree and rough sets to generate rules from statistical features extracted from vibration signals under good and faulty conditions of a mono block centrifugal pump. A fuzzy classifier is built using decision tree and rough

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set rules, tested and the results are compared with those generated by a PCA based decision tree-fuzzy classifier. Sakthivel et al. [25] reported the use of statistical features extracted from time domain signals for classification of faults in centrifugal pumps using decision tree. For the fault classification of mono block centrifugal pump, Sakthivel et al. [26] have used artificial immune recognition system (AIRS). The fault classification efficiency of AIRS is compared with hybrid systems such as PCA-Naïve Bayes and PCA-Bayes Net. AIRS was found to outperform other hybrid systems. Wang and Chen [31] introduced a fault diagnosis method for a centrifugal pump with frequency domain symptom parameter using wavelet transforms for feature extraction, rough sets for rule generation and fuzzy neural network for classification to detect faults and distinguish fault types at early stages. Rafiee et al. [20] illustrated an artificial neural network (ANN)-based procedure for fault detection and identification in gearboxes using a new feature vector extracted from standard deviation of wavelet packet coefficients of vibration signals. The use of vibration signals requires minimum instrumentation but the use of wavelet transforms increases the computational requirements. M. Zhao et al. [42] employed TR-LDA based dimensionality reduction technique for fault diagnosis of rolling element bearings. Y. Zhang et al. [37] proposed an improved manifold learning algorithm by combining adaptive local linear embedding and recursively applying normalised cut algorithm for nonlinear dimensionality reduction, which was then proven to be effective in dealing with standard test data sets as well as on the Tennessee–Eastman process. D.Q. Zhang et al. [36] proposed an efficient dimensionality reduction algorithm called semi supervised dimensionality reduction. Zhang et al. [38–40] presented a novel feature extraction technique called group sparse canonical correlation analysis (GSCCA). M.S. Baghshah et al. [2] proposed a kernel based metric learning technique that can produce nonlinear transformation of the input features resulting in better learning performance. Zhang et al. [38–40] proposed an improvement over the Isomap dimensionality reduction technique called the Marginal Isomap (M-Isomap) which was able to provide better separation of data clusters. F.P. Nie et al. [17] developed an algorithm to find the global optimum for the orthogonal constrained trace ratio problem. Yaguo Lei et al. [33] proposed a system for fault diagnosis of rolling element bearings based on empirical mode decomposition (EMD), an improved distance evaluation technique and the combination of multiple adaptive neuro-fuzzy inference systems (ANFISs). Van Tung Tran et al. [30] discussed a combined fault diagnosis system for induction motor based on classification and regression tree (CART) algorithm and ANFIS. Yaguo Lei [34] proposed fault diagnosis of rotating machinery based on statistic analysis and ANFIS. Necla Togun and Sedat Baysec [16] presented the application of genetic programming (GP) to predict the torque and brake specific fuel consumption of a gasoline engine. In the work reported by Demetgul [5] fault diagnosis of pneumatic systems using ANN was presented.

However, to the best of our knowledge, the comparison of traditional dimensionality reduction techniques with nonlinear dimensionality reduction techniques for fault classification of a mono block centrifugal pump has not been reported so far. This paper investigates traditional dimensionality reduction technique PCA and the following nine nonlinear dimensionality reduction techniques: (1) Kernel PCA, (2) Isomap, (3) Maximum Variance Unfolding, (4) diffusion maps, (5) Locally Linear Embedding, (6) Laplacian Eigenmaps, (7) Hessian LLE, (8) Local Tangent Space Analysis, and (9) manifold charting. These dimensionality reduction techniques are used to transform statistical features extracted from the pump vibration signals. Decision tree, naïve Bayes Bayes Net and kNN classifiers are then used to classify the faults. The main objectives of the work are:

(i) To investigate to what extent the nonlinear dimensionality reduction techniques outperform the traditional PCA on centrifugal pump data sets
(ii) To find out the best dimensionality reduction technique–classifier combination.

2. Experimental studies

2.1. Experimental setup

Fig. 1 shows the schematic diagram of the experimental test rig. The motor (2HP) drives the pump. The control valve is used to adjust the flow at the inlet and the outlet of the pump. The inlet valve is used to create pressure drop between the suction and at the eye of the impeller to simulate cavitation. An accelerometer mounted at the eye of the impeller (location shown in Fig. 1), is used to measure the vibration signals. This is due to the fact that the mechanical components under consideration in the present study (seal, impeller, bearing), are located close to the eye of the impeller.

2.2. Experimental procedure

The vibration signals are acquired from the centrifugal pump working under normal condition at a rated speed of 2880 rpm. Centrifugal pump specification is shown in Table 1. Vibration signals from the accelerometer are measured. The sampling frequency is 24 kHz. 250 sets of readings are taken for each centrifugal pump condition.

In the present study, the following faults are simulated

Bearing fault – Inner and Outer race fault
Seal fault – Broken seal
Impeller fault – Damaged impeller
Bearing and Impeller fault together
Cavitation – at the eye of the impeller

The faults are introduced one at a time and the pump performance characteristic and vibration signals are taken.

3. Feature extraction

Statistical analysis of vibration signals yields different descriptive statistical parameters. The statistical parameters taken for this study are mean, standard error, median, standard deviation, sample variance, kurtosis, skewness, range, minimum, maximum, and sum. These eleven features are extracted from vibration signals.

4. Dimensionality reduction techniques [14]

4.1. Linear dimensionality reduction techniques

4.1.1. Principle component analysis (PCA)

PCA is a linear technique for dimensionality reduction. It performs dimensionality reduction by embedding the data into a linear subspace of lower dimensionality. PCA is one of the most popular (unsupervised) techniques. Therefore, PCA is included in this comparative study.

PCA constructs a low-dimensional representation of the data that describes as much of the variance in the data as possible. This is done by finding a linear basis of reduced dimensionality for the data, in which the amount of variance in the data is maximal. The basic working of a PCA is presented below.

Let $x_1, x_2,\ldots, x_n$ be $N \times 1$ vectors