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# Improving the performance of univariate control charts for abnormal detection and classification

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## ABSTRACT

Bearing failures in rotating machinery can cause machine breakdown and economical loss, if no effective actions are taken on time. Therefore, it is of prime importance to detect accurately the presence of faults, especially at their early stage, to prevent sequent damage and reduce costly downtime. The machinery fault diagnosis follows a roadmap of data acquisition, feature extraction and diagnostic decision making, in which mechanical vibration fault feature extraction is the foundation and the key to obtain an accurate diagnostic result. A challenge in this area is the selection of the most sensitive features for various types of fault, especially when the characteristics of failures are difficult to be extracted. Thus, a plethora of complex data-driven fault diagnosis methods are fed by prominent features, which are extracted and reduced through traditional or modern algorithms. Since most of the available datasets are captured during normal operating conditions, the last decade a number of novelty detection methods, able to work when only normal data are available, have been developed. In this study, a hybrid method combining univariate control charts and a feature extraction scheme is introduced focusing towards an abnormal change detection and classification, under the assumption that measurements under normal operating conditions of the machinery are available. The feature extraction method integrates the morphological operators and the Morlet wavelets. The effectiveness of the proposed methodology is validated on two different experimental cases with bearing faults, demonstrating that the proposed approach can improve the fault detection and classification performance of conventional control charts.

*Abbreviations:* SNR, Signal-Noise Ratio; SVD, Singular Value Decomposition; SV, Singular Value; FC, Center Frequency; CSMW, Complex Shifted Morlet wavelet; EWMA, Exponentially Weight Moving Average; MSPC, Multivariate Statistical Process Control; MM, Mathematical Morphology; MO, Morphological Operator; BG, Beucher Gradient; SF, Shape Factor; KU, Kurtosis; RMS, Root Mean Square; CF, Crest Factor; SMF, Shape Modified Form; ESPRIT, Estimation of Signal Parameters via Rotational Invariance Techniques; ENKU, ENvelope form through KUrtogram; IFESIS, Instantaneous Frequencies Estimation via Subspace Invariance properties of wavelet Structures; SE, Structuring Element; CL, Center Line; LCL, Lower Control Limit; UCL, Upper Control Limit; KUC, Kurtosis Criterion; FFT, Fast Fourier Transform; IFFT, Inverse Fast Fourier Transform; CUSUM, CUmulative SUM; SPC, Statistical Process Control; OR, Outer Race; IR, Inner Race; MSV, Mean Singular Value; WCF, Wavelet Center Frequency; MW, Morlet Wavelet; BPFO, Bearing Pass Frequency Outer; BPFI, Bearing Pass Frequency Inner; RF, Raw Form; SORDINA, SOurce fRequency Detection via INvariance Approach; IF, Instantaneous Frequency; FT, Fourier Transform

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## 1. Introduction

Bearing diagnostics has been a topic of intensive research for many years, presenting development and improvement of novel signal processing tools and algorithms for failure (anomaly) detection, classification and prediction, aiming at early and accurate fault detection in rotating machinery. The methods can be included in a framework of predictive maintenance focusing towards the increase of useful components life and the prevention of economic loss and catastrophic accidents. Feature extraction is one of the most basic steps in the fault diagnosis procedure. The signals emitted by rotating machinery are usually non-stationary, non-linear and with strong noise interference while the early signal energy is too low to extract fault features in time domain. In order to extract optimal features in low signal-to-noise ratio (SNR) environments, it is an urgent demand to develop effective and versatile signal processing tools which can be adapted to different applications and operating conditions. The widespread applications of rolling element bearings have inspired the emerging of many advanced technologies to monitor their health status. As a consequence, the last decades have seen the rapid advancement of feature extraction methods [1–8], such as time-domain methods, frequency domain methods and time-frequency methods, which are capable of extracting the most representative features and simultaneously decreasing their dimension in order to maximize the effectiveness and the accuracy of the classification methods.

In this work, the singular value is the extracted feature, used for novelty detection. This feature has not been widely used in the area of the engineering [9–12]. Kang et al. [9] introduced a robust feature extraction method to achieve high classification even in a noisy environment. The proposed method combines the Short-Time Energy with the Singular Value Decomposition (SVD) technique producing simple features used in a wide variety of classification schemes but the irregular patterns of their values can lead to low classification accuracy. For this reason, the SVD-based feature extraction approach is applied to overcome this limitation. The original signal is divided into sub-bands, the feature values are calculated in each sub-band and a matrix is composed. Afterwards, this matrix is decomposed using SVD. The Singular Values (SVs) are used as features to categorize the faults.

A new fault feature approach is introduced in [10]. This work is based on the Singular Spectrum Analysis of the vibration signal that is implemented in order to decompose the acquired signals into an additive set of principal components. Initially, the vibration signal is mapped into a sequence of multidimensional lagged vectors resulting to a trajectory matrix. This matrix is decomposed through SVD into a sum of mutually orthogonal, unit rank, elementary matrices. The obtained SVs, set in decreasing order, are used to form a Singular Spectrum. Then, the Singular Spectrum plots for different bearing conditions are compared and the appropriate SVs are selected. Finally, they are adopted as inputs to an artificial neural network for fault diagnosis.

However, most of the available datasets are captured during normal operating conditions. Additionally, an inevitable consequence of the high degree of system complexity is the large number of possible failure modes, the effects of which on observable data are often poorly defined. Thus, there are insufficient examples of failure to construct accurate fault-detection systems. As a result, conventional fault-specific failure-detection schemes are usually limited to identifying a small subset of known, well-understood modes of failure. An alternative to identifying rare and unexpected modes of failure is the novelty detection approaches [13–15], where a model of normality is constructed from normal system data. Departures from abnormal behavior are classified as novel events. Novelty detection is alternatively known as one-class classification, outlier detection or anomaly detection. Being novelty detection methods able to work when only normal data are available, such methods are of considerable promise for health monitoring in the case of lacking fault samples and prior knowledge.

A number of classifiers (Gaussian Mixture Models, Hidden Markov Models, kNN-based, etc) have been adapted for novelty detection [16–19]. It has been realized in practice that the novelty detection is an extremely challenging task. As a result several novelty detection models have been proposed performing well on specific data sets. It is clearly evident that till now there is no global best model for novelty detection and the success depends not only on the type of the method used but also on the statistical properties of data handled.

In this study, conventional control charts are applied and configured for successful anomaly detection. In contrast to condition monitoring and fault diagnosis of rotating machinery, monitoring of chemical processes using conventional control charts has been reported in literature by many researchers [20]. In industrial processes, conventional control charts such as Shewhart control chart are well established for the monitoring of univariate processes. In order to monitor multivariable processes, multivariate statistical process control (MSPC) has been developed such as the Hotelling $T^2$ control chart for correlated variables.

A recent work about fault detection in mechanical engineering systems using control charts has been presented by Zhou et al. [21]. The researchers developed a damage detection scheme by integrating the recurrence plot method and $T^2$ control chart. Five types of features are extracted by the recurrence quantification analysis to quantify the vibration signal characteristics. Then, a novel $T^2$ bootstrap control chart is applied to monitor these features.

In this paper, a novel type of diagnostic features is proposed combining the morphological analysis and the Complex Shifted Morlet Wavelets. The extracted singular values are adopted as the optimal features. Then, the features are further used as inputs to univariate control charts focusing towards an early abnormal change detection and classification, under the assumption that measurements under normal machine operating conditions are available. The rest of the paper is organized as follows: the basic theory of the morphological analysis, the Complex Shifted Morlet Wavelets, the IFESIS and the SORDINA are summarized in Section 2. The complete hybrid methodology is presented in Section 3. The effectiveness of the proposed hybrid method is validated in Section 4, using two different experimental cases with bearing faults that are available online at the Prognostics Center of Excellence [22]. Finally the conclusions of this work are briefly mentioned in Section 5.