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# A new rolling bearing fault diagnosis method based on multiscale permutation entropy and improved support vector machine based binary tree

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A B S T R A C T

A new bearing vibration feature extraction method based on multiscale permutation entropy (MPE) and improved support vector machine based binary tree (ISVM-BT) is put forward in this paper. Local mean decomposition (LMD), a new self-adaptive time–frequency analysis method, is utilized to decompose the roller bearing vibration signal into a set of product functions (PFs) and then MPE method is used to characterize the complexity of the principal PF component in different scales. After the feature extraction, a new pattern recognition approach called ISVM-BT is introduced to accomplish the fault identification automatically, which has the priority of high recognition accuracy compared with other classifiers. Besides, the Laplacian score (LS) is introduced to refine the fault feature by sorting the scale factors. Finally, the rolling bearing fault diagnosis method based on LMD, MPE, LS and ISVM-BT is proposed and the experimental results indicate the proposed method is effective in identifying the different categories of rolling bearings.



## 1. Introduction

Rolling bearings are important and fragile parts in the industry filed and bearing health monitoring research has attracted considerable attention in recent years [1]. Among them, the vibration analysis method has been widely applied for diagnosing the rolling bearing fault due to its intrinsic merits of revealing bearing failure [2,3]. It is generally accepted that vibration analysis method consists of two major aspects: fault feature extraction and fault pattern classification [4].

Since the measured vibration signal often represents nonlinear and non-stationary characteristics, much research in recent years has been focused on time–frequency analysis techniques [5]. The current time–frequency analysis techniques are mainly composed of two classes. The first one is that some parameters needed to be set before analyzing the vibration signal, such as wavelet transform (WT). A multi scales time series can be decomposed into scale time–frequency components by using WT [6]. However, the wavelet basis function is needed to predefined, and different choices of the wavelet basis function will have great influence on final results. Therefore, WT doesn't have the nature of self-adaptive feature. The second one is self-adaptive time–frequency decomposition technique, the well-known example is empirical mode decomposition method (EMD) [7]. EMD can self-adaptively decompose any complicated signal into sum of intrinsic mode functions (IMFs) according to natural oscillations embedded in the vibration signal, which is a totally self-adaptive vibration analysis technique. However, although the effectiveness of EMD on the rolling bearing fault diagnosis has been

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demonstrated by many applications [8], it has the end effect and mode mixing problems [9].

Recently, a new self-adaptive time–frequency analyzing method, local mean decomposition (LMD) was proposed by Smith in 2005 [10], which can automatically decompose a multi-component amplitude-modulated and frequency-modulated (AM–FM) signal into a number of product functions (PFs) and each PF is a mono-component AM–FM signal. Also, the comparisons of LMD and EMD have been done, and the merits of the LMD have been verified [3,11]. It is generally accepted that the measured vibration signal of rolling bearing often exhibits AM–FM feature under fault conditions. Therefore, LMD is suitable for processing the roller bearing fault vibration signal.

After LMD decomposition, a major current focus is how to extract the fault information from the obtained PF components. Many studies have been conducted to investigate the feature extraction methods. Approximate entropy (ApEn) was put forward by Pincus [12], it was introduced to monitor the rolling bearing health conditions by Yan and Gao [13]. However, ApEn is heavily relied on the data length and its estimated value is uniformly lower than that expected ones when processing the short dataset. To overcome the weakness of ApEn, Richman and Moorman proposed Sample entropy (SampEn) [14]. Due to the SampEn value is insensitive to the data length and immunity to the noise in the data, it has attracted a great deal of attentions. However, SampEn and ApEn estimate the complexity at a single scale, which give rise to unacceptable result when applied to analyze the multiple time scales data. In regard to this disadvantage, Costa [15] put forward a multi-scale entropy procedure to estimate the complexity of the original time series over a range of scales. Multiscale entropy (MSE) has been one of the most effective methods that explicitly explained the multiple time scales inherent in complex vibration signals. However, MSE can cause a bad estimation of complexity to the practical measured bearing fault vibration signals, and it is time-consuming especially processing the long time series.

Recently, a new entropy called permutation entropy (PE) was proposed by Bandt to measure the complexity and assess the status of the mechanical system [16]. Since the PE method measures the complexity through comparing the neighboring values, it is simple, immune to noise, and suitable for online monitoring. PE has been widely applied in the signal analysis, such as rolling bearing vibration signals [17,18] and electroencephalography (EEG) signal analysis [19]. Based on the PE method , multiscale permutation entropy (MPE) was proposed by Aziz and Arif [20], which was used to estimate the complexity of the time series in different scales. Also the advantages of MPE have been validated, such as stability and robustness. In addition, Wu used MPE and SVM to diagnose the rolling bearing fault, and verified that the MPE has better performance compared with PE [17].

Therefore, MPE is taken as a feature extractor to extract the fault information from the vibration signals in this paper. After extracting the fault features using MPE, the obtained features are fed into SVM classifier to accomplish the fault diagnosis. However, the feature vectors obtained from vibration signals using MPE are high dimension with information redundancy, which will make the diagnosis accuracy decreasing and time-consuming. An effective approach to select $m$ most important scale factors to construct the fault feature vectors is necessary. The Laplacian score (LS) proposed by He et al. is introduced in this paper [21]. The approach aims to choose the most important features that exhibit high divisibility and contain the most important fault information from the obtained features of MPE. The fault feature vectors can be automatically ranked according to their importance and correlations with the main fault information by using LS [4,22], and then we select $m$ most important scale factors to construct the fault feature vectors. The LS is taken as a refining tool, which can not only reduce the data dimension but also enhance the identification accuracy greatly.

Naturally, after extracting feature vectors using MPE, the multi-fault classifier is needed to automatically conduct the fault diagnosis. Since support vector machine (SVM) is effective in making a reliable decision for a smaller number of dataset and good generalization capabilities, SVM is adopted to fulfill the mechanical fault diagnosis. There are varieties of techniques for solving the multi-class problem based on SVM, such as: one against one (OAO) [13], one against all (OAA) [23], decision directed acyclic graph SVM (DDAGSVM) [24], One-Versus-All (OVA) [25] and support vector machines based on binary tree (SVM-BT) [26].

As alternative approach to other classifiers, SVM-BT has the advantages as follows: fewer sub-classifiers, none of unclassifiable region and good classification performance [26]. A major concern of SVM-BT is the adoption of hierarchical structures for the training of a multi-class SVM, which is vitally important for classification performance. In this paper, we introduce a novel hierarchical structures design for SVM-BT, called improved SVM-BT (ISVM-BT), which is based on the combination of inter-class Euclidean distance (ED) and intra-class sample distribution. ISVM-BT can reflect the class separability more comprehensively and improve the classification accuracy obviously and the superiority of the ISVM-BT is verified by the standard dataset.

The contributions of the work reported in this letter in the field of rolling bearing fault diagnosis are summarized as follows:

1. Rolling bearing feature extraction from noise-contaminated sensor signals based on LMD and MPE.
2. Design of a new hierarchical structures in the SVM-BT, which leads to the significant performance enhancement.
3. Real-time pattern classification based on LS and ISVM-BT.

The rest of this paper is organized as follows. Section 2 gives the main steps of LMD. Section 3 describes the basis of PE and MPE and discusses the effect of each parameter of MPE. Section 4 presents the feature selection method based on LS. Section 5 introduces the ISVM-BT method, meanwhile, the superiority of ISVM-BT is validated. Section 6 illustrates the proposed feature extraction method based on LMD, MPE, LS and ISVM-BT and instantiates the classification performance of the proposed method under