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# Feature Vector Selection Method Using Mahalanobis Distance for Diagnostics of Analog Circuits Based on LS-SVM

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**Abstract** Multi-fault diagnosis for analog circuits based on support vector machine (SVM) usually used a single feature vector to train all binary SVM classifier. In fact, each binary SVM classifier has different classification accuracy for different feature vectors. However, no one has discussed the optimal or near-optimal feature vector selection problem. Based on Mahalanobis distance, a near-optimal feature vector selection method has been proposed for diagnostics of analog circuits using the least squares SVM (LS-SVM). The selection problems of wavelet types, wavelet decomposition level, and normalization methods have been also discussed. Two filters with parametric faults and a nonlinear half-wave rectifier with hard and parametric faults were used as circuits under test (CUTs). The simulation results showed the following: (1) the accuracies using the feature vector with the maximum MD were better than the average accuracies using all the feature vectors, and were better than most accuracies using a single feature vector. But the computation time using the MD method was an order of magnitude larger than that using a single feature vector; (2) Most the diagnostic accuracies using the maximum MD method were near to the optimal accuracies using the exhaustive method while the computation time was reduced about 20–50 % in comparision to the exhaustive method; (3) the Haar wavelet was the best choice among Daubechie's wavelet family for all CUTs' diagnosis; (4) only non-normalization, all-normalization, and part-normalization methods are necessary to be considered for feature vector normalization. The proposed method can obtain a near-optimal diagnostic accuracy in a reasonable time, which is beneficial for analog IC or circuits testing and diagnosis.

**Keywords** Analog circuits · Diagnostics · Feature vector selection · Mahalanobis distance · Near-optimal · Least squares support vector machine (LS-SVM)

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## 1 Introduction

Fault diagnosis and fault location in analog and mixed signal circuits are important issues for design validation and prototype characterization [16]. In contrast to the well-developed automatic fault diagnosis methodologies for digital circuits, diagnostics of analog circuits is far less advanced due to poor fault models, component tolerances, and nonlinearity issues of analog circuits [2, 21]. The conventional fault models for analog cirtuis are catastrophic or hard faults models, where an analog component becomes open or shorted, and the parametric faults, where the value of a component such as *R*, *L* and *C* or the value of a transistor parameter (transconductance, etc.), changes sufficiently outside of the tolerance limits and causes unacceptable circuit performance [3, 17]. Diagnostic methods for analog circuits are classified into two categories [3]: simulation before test (SBT), and simulation after test (SAT). SBT is more accepted in industry because only one off-line computation is required before test activities [8]. Among SBTs, data-driven diagnostic methods, such as neural networks (NNs) and support vector machines (SVMs), are more suitable for diagnostics of analog circuits because they do not need an explicit model [1, 2, 4, 5, 11, 12, 19, 22]. Considering the trade-off between learning ability and generalizing ability by minimizing structure risk, support vector machines (SVMs) have been shown to be an effective tool for the diagnostics of analog circuits [6, 10–14, 19, 23, 24].

Feature selection methods have become an apparent need for diagnostic methods such as SVMs. Zhang et al. [23] and Liu et al. [10] directly used output voltage as features to train a SVM classifier for diagnostics of analog circuits. The SVM classifier without preprocessing methods often results in longer training time and less classification accuracy than a classifier with preprocessing ones. Cui and Wang [6] have used wavelet transform coefficients as features for diagnostics of a half-wave rectifier. Long et al. [12] and Zuo et al. [24] have developed the energy indicators of wavelet transform coefficients as features to train the least squares SVMs (LS-SVMs), which reduces the computation complexity of traditional SVMs by adding a least squares term in the cost function [18]. For the preprocessing method based on wavelet transform, it is difficult to decide what type of wavelet function and which level of wavelet decomposition should be used. Recently, Long et al. [11, 13, 14, 19] have proposed many feature vectors for diagnostics of analog circuits based on LS-SVMs. These feature vectors included two new feature vectors with clearly defined meanings based on time-domain response curves and frequency response curves [11, 19], various kinds of wavelet feature vectors [13, 14], and a statistical property feature vector which was composed of mean, stand deviation, skewness, kurtosis, and entropy of the response curve [11, 14].

Multi-fault diagnosis for analog circuits based on SVM are typically solved by combining many binary SVM classifiers, such as one-agaist-one SVM, one-against-all SVM, and directed acyclic graphic SVM [7]. Most researchers [6, 10–14, 19, 23, 24] used a single feature vector to train all SVM binary classifiers. In fact, each SVM binary classifier has different classification accuracy for different feature vectors. The Mahalanobis distance (MD) [6] [9, 15, 20] is an useful way of determining similarity of an unknown sample set to a known one. MD is based on correlations between variables by which different patterns can be identified and analyzed. Generally, the two data set are more similar, and more difficult to classify if their MD value is smaller. The optimal feature vector could have the capability to distinguish between two fault classes. So we can use the feature vector with maximium MD to train and test LS-SVM classifier for any two fault classes of analog circuits.

This paper will focus on selecting a near-optimal feature vector with the maxiumium MD to diagnose faults in analog circuits based on LS-SVM. A biquad lowpass filter with parametric faults, a Sallen-Key bandpass filter with parametric faults and a nonlinear half-wave rectifier with hard faults and parametric faults were used as circuits under test (CUTs) in this paper. The paper is organized as follows: Section 2 presents the diagnostic procedure for analog circuits based on LS-SVM. Section 3 briefly reviews some feature vectors of analog circuits based on time-domain and frequency response curves. Section 4 proposes anear-optimal feature vector selection method based on MD. Section 5 shows the simulation results for the three example circuits. Section 6 presents our conclusions.

## 2 A Diagnostic Procedure Based on LS-SVM

A diagnostic procedure for analog circuits based on LS-SVM involves four phases: data collecting phase, preprocessing phase, training phase, and diagnostic phase, as shown in Fig. 1. Data collecting for simulation data or real data is a time-consuming work, but it is not too difficult in technique. In the training phase and diagostic phase, a well-made LS-SVM toolboxs, such as LS-SVMlab toolbox [18], can be directly used in the diagnostics of analog circuits. The LS-SVMlab toolbox can help us avoid duplicated work in SVM and make the diagnostic program more reliable. Therefore, the key to the diagnostic procedure is the preprocessing phase, which will focus on how to define the feature vectors of CUTs and how to select a near-optimal feature vector to train LS-SVM classifier. These two problems in the preprocessing phase will be detailed in Section 3 and Section 4. Details of a diagnostic procedure for diagnostics of analog circuits based on LS-SVM can be found in [11, 13, 19].

## 3 Feature Vectors of Analog Circuits

The feature vectors to train LS-SVM for diagnostics of analog circits can be mainly classified into four categories: (1) wavelet feature vectors [6, 12–14, 24]; (2) statistical property feature vectors [11, 14]; (3) conventional time-domain feature vectors [11, 14]; and (4) conventional frequency feature vectors [11, 13, 19]. We give a brief review of these feature vectors below.

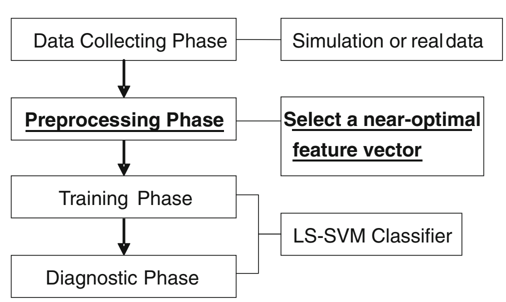


**Fig. 1** A diagnostic procedure based on LS-SVM