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Motor bike piston-bore fault identification from engine noise signature analysis

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ABSTRACT

Imitation of the act of diagnosing engine faults by an expert auto-mechanic just by hearing the noise from a defective vehicle has been attempted with a robust instrumentation technique. In the present experimental work, the prime objective is to establish a process to identify the piston-bore defect by analyzing the engine noise. The aim is to develop a robust filtering algorithm in order to be able to use the technique in the natural environment of an auto workshop. The algorithm uses engine noise data from healthy and defective vehicles acquired in the natural workshop environment. Effectiveness of conventional parameters that are used (six of the most preferred) in statistical learning systems to tackle similar problems has been assessed. Additionally, six more statistical parameters have been derived and proposed to achieve a more effective statistical-learning based decision making system. These additional parameters have been derived from the continuous wavelet transform (CWT) coefficients. The appropriate coefficient level has been decided by using the frequency marginal integration of the CWT coefficients. A deeper level of CWT scalogram analysis has been carried out to establish the appropriateness of complex Morlet wavelet function, for the class of problem under investigation. Then the proposed technique uses a third degree polynomial kernel function and sequential optimization based support vector machine (SVM) based on all the twelve parameters in order to identify the piston-bore defect from engine noise signature. It has also been shown that Feed-forward Back-propagation Neural Network (FBNN) is equally effective with higher number of training samples.

1. Introduction

Health monitoring of motor vehicle engines is of paramount importance, as their physical condition is directly responsible for the quality of the exhaust of the vehicle. This is even more crucial in countries like India where the number of two wheelers is enormously high and the general maintenance practice is abysmally poor. The main reason for this is the lack of infrastructure for regular and frequent inspection of the emission level of the vehicles. An on-board continuous exhaust monitoring system is not practical form the implementation point of view. However, other parameters which can be directly correlated to the quantity and quality of the emission can be monitored on a continuous basis. Noise from the engine of a vehicle is one such parameter that can provide vital information about its health and this aspect has been addressed in the present work.

Acoustic signal, as a parameter, has many advantages over conventional parameters. Acoustic signal can be acquired with a non-intrusive, non-consumable and long lasting instrumentation. Furthermore, the acoustic signal has been tested to be very useful in condition monitoring and fault diagnosis of many types of system including reciprocating and rotating machineries [1,2]. Wu and Chen have investigated and reported the effectiveness of the continuous wavelet transform technique in fault signal diagnosis of internal combustion engines and its cooling system [3]. Albarbar et al. have investigated diesel engine air-borne acoustic signals characteristics and the benefits of joint time–frequency domain analysis. The fuel injection process characteristics have been identified in the time–frequency domain using Wigner-Ville distribution (WVD) technique [4]. Albarbar et al. also have reported the details about operating conditions of an internal combustion engine and its corresponding engine noise signal correlation in a normal, acoustically untreated laboratory environment, without any sound measurement precautions [5]. One can find many interesting applications of acoustic based fault diagnosis systems such as exhaust valve leakage, fuel injection behavior, and various aspects of the combustion process [6–10] to name a few.

In the present work the most common engine defect, commonly branded as the piston-bore defect which is known to have direct impact on the quality of the exhaust, has been addressed. This work has been inspired by the near super-human ability of auto

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mechanics in identifying this defect just by carefully listening to the sound coming from the vehicle. Therefore, in an attempt to mimic their working style, a methodology has been established that broadly follows the stages of appropriate signal filtering, statistical learning and feature based classification.

In order to study the state of the art of signal filtering for this kind of problems with an aim to suggest the most appropriate technique a through literature study has been carried out. It is a well known fact that the non-stationarity in the acoustic signal over a single rotation period gets altered significantly in presence of defect in rotating or reciprocating machines. In recent years, many researchers investigated various methods for signal processing of non-stationary acoustic signals for fault diagnosis and condition monitoring purpose [11,12]. Classical frequency domain parameters like power spectral density (PSD), provides adequate information concerning frequency components that are present in the acoustic signal. However frequency information alone is not adequate when it comes to analyze non-stationary signals, where a good time–frequency resolution is highly desired to map defect conditions to the variations in the signal. The time frequency analysis (TFA) provides a revealing framework for the inspection and classification of non-stationarity in acoustic signals [13]. The selection of the feature extraction technique in the time frequency domain, and the method for feature classification highly hinges on application specific requirements. There is no single scheme, which can be accepted to be optimal solution technique for all practical applications. From literature one can find that the continuous wavelet transform (CWT) of acoustic signals is a promising method to obtain the time–frequency energy distribution of a signal [14]. Even so, the selection of appropriate mother wavelet function for any particular situation remains a challenge for the researchers [15,16]. Of late, another aspect of condition monitoring captured the interest of researchers in this field. This aspect deals with automatic defect identification and classification which primarily aims to realize online machine health monitoring systems using concepts like Artificial Neural Network (ANN) and support vector machine (SVM).

In recent years, significant improvements have been reported based on artificial neural network (ANN), support vector machine (SVM), Wigner-Ville distribution (WVD) and continuous wavelet transform (CWT) etc. for condition monitoring of various types of rotating machines. Their relative strengths and weaknesses dictate their application in specific situations. For example, Wu and Liu have reported an expert system for fault diagnosis of internal combustion engines using wavelet packet transform coefficients. Using these coefficients, the entropy of the signal is evaluated and taken as input features in order to the ANN to identify the fault [17]. Tang et al. have proposed the cross validation method (CVM) to optimize the wavelet scale factor, and the auto terms window (ATW) to suppress the cross terms in WVD of the denoised signal [18]. Konar and Chattopadhyay have presented a bearing fault detection scheme of three-phase induction motor using SVM along with CWT at narrow range of scale [16]. Porteiro et al. have used the capability of an ANN exclusively on data obtained from nonintrusive sensors to determine the load and condition of a diesel engine [19]. Barad et al. have used ANN approach for a combined performance and mechanical health monitoring of a gas turbine engine [20]. Summarizing, the ANN has been tested to be effective in defect identification/classification, where as CWT and WVD are suitable to filter and analyze the non-stationary in rotating machine signals adequately.

On shifting the focus to the identification through classification techniques, one can find a few motivating works. Gryllias and Antoniadis have implemented SVM for rolling element bearing fault detection in industrial environments. Frequency domain parameters of the raw vibration signal and demodulated signal are used as inputs to the SVM classifier to separate the normal condition from the faulty one followed by a classification of the types of the fault [21]. Matic et al. have used SVM for fault diagnosis of broken bar in electrical induction machines. The two dimensional feature space, i.e., the magnitude and the frequency of the characteristic peak from the spectrum of the Hilbert transform series of the phase current is used to train the SVM [22]. In another interesting work, Elangovan et al. have described the efficiency of Radial basis kernel function in SVM for fault diagnosis of a single point cutting tool [23]. The linear kernel is suitable for instant classification whereas the 2nd degree polynomial kernel is far more effective than all other combinations when the combined effect of result quality and the processing time are considered. From the literature, it is clear that every system, though they belong to the common category of rotating machinery components, is unique in itself and requires formulation of signal processing methodology pertinent to the system under investigation.

In summary, the piston-bore defect identification based on engine noise signature has not been addressed profoundly. Although, various methodologies have been proposed for acoustic based condition monitoring of similar applications, suitability of such techniques are highly reliant on the type of application and the quantity and quality of parameters that are needed to be monitored. From literature, it is also worth noticing that when expert systems are developed using experimental data, robustness of such systems depend crucially on the nature of the signal signatures and the total number of training samples.

In the present work, the engine noise signal from both a healthy and a defective vehicle have been captured in the natural auto-workshop environment. As the name of the fault suggests, this defect involves faulty piston and/or cylinder bore. A sample of a defective piston-bore pair of a vehicle is shown in Fig. 1. After this present in Section 1, Section 2 explains some basic theory related to the proposed algorithm. Sections 3 presents general experimental set-up and the data acquisition system for acquiring engine noise signal from the vehicle engines. Section 4 presents various results from the proposed method for its validation. The same section establishes a robust expert system for defect identification as well. The last section, then concludes the entire work by summarizing the exact methodology with prominent observations and important suggestions for tackling the problem at hand.

2. Brief overview on proposed algorithm

The proposed method consists of two phases of defect identification. In the first phase, the defect localization in the continuous wavelet transform (CWT) spectrum is carried out. The complex Morlet wavelet has been shown to be appropriate for the present application, particularly over bi-orthogonal wavelet. Next, the supervised statistical learning mechanisms have been carried out. A variant from artificial neural network (ANN) and support vector machine (SVM) have been implemented to establish a robust expert system suitable for natural workshop environment.

2.1. Defect localization using Continuous Wavelet Transform (CWT)

Predictably, the noise signal from the vehicle engine are not stationary in nature over any particular period. However, the requirement of understanding the periodicity of the acoustic signal burst due to defect and the associated frequency components calls for a joint time frequency analysis. With a given family of basis functions, the dilated and translated wavelets can be used to formulate a signal processing technique for localizing both time and frequency. These functions can be modeled by the linear combination