Acoustic-based diagnostics of belt conveyor idlers in real-life mining conditions by mobile inspection robot

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Abstract

Belt conveyors are commonly used for the transportation of bulk materials, mainly in mining industry. Due to the number of idlers to be monitored, the size of the conveyor, and the risk of accidents when dealing with rotating elements and moving belts, monitoring of all idlers (i.e. using vibration sensors) is impractical regarding scale and connectivity. The application of the inspection robot can "replace" the classical measurement done by maintenance crews. In this paper, a method based on application of mobile inspection robot for capturing acoustic signals instead of commonly used vibrations is proposed. Furthermore, the authors show that damage detection in bearings of idlers using acoustic data is possible, even in the presence of a significant amount of background noise. Influence of the sound disturbance due to the belt joints and other factors can be minimized by appropriate signal processing methods.

1 Introduction

Services of industrial infrastructures in mines rely on data that are collected regularly through manual or semi-automatic inspection processes. In some equipment such as conveyor systems, semi-automatic condition monitoring systems can be only applied on a limited scale. Drive units (engine, gearbox, etc.) can be monitored by supervisory control and data acquisition (SCADA) methods while other modules such as belt surface and idlers need to be manually inspected by maintenance crew [1, 2, 3]. Robotics-based inspection solutions are capable of replacing inspection crew roles in harsh environments. At present, we already have ready-made mass examples of robotized processes in open-cast mines while applications of inspection robots in underground mines are still limited [4].

In the major mining sites, conveyor systems are the most common way for transportation of raw materials over long distances. Conveyor systems should be operated nearly 24 h/day under harsh environmental conditions therefore, to reduce the risks of a sudden breakdown in transportation networks, all parts of a belt conveyor should be regularly inspected [2, 5]. In practice, conveyors are distributed over a large area in severe environmental conditions (potential gas hazard, high temperature, humidity, etc.) where, inspectors must walk many kilometers to manually inspect the conveyor modules [6, 7].

Visual inspection, thermal imaging, and acoustic measurements are among the popular ways for condition monitoring of idler modules in conveyor systems [8, 9, 10]. Collecting the accosting signals from rotating idlers can be considered a significant innovation in condition monitoring of conveyor systems [2, 11, 12, 13, 14].

The fault detection methods in rolling element bearings have been widely discussed in the literature[15, 16, 17] however, the Application of acoustics-based fault detection methods in rolling element bearings is rarely explored [18, 19, 20, 21].

In [11, 22, 23, 24, 25] researchers discussed the approach based on advanced cyclostationary techniques for analyzing acoustic signals that contain non-gaussian noises. The cyclostationary analysis method is recognized as the most intuitive and powerful signal analysis technique that focused on rolling element bearings diagnostics. It can be considered an early-stage fault detection technique that is mostly performed for vibration and acoustic signals to find hidden periodicity in the observation.

In this paper, we proposed a combination of robotics-based inspection methods together with acoustic data measurement and a novel signal processing procedure for fault detection in idlers. The captured acoustic data by the inspection robot have been processed by cyclostationary methods. Furthermore, the acquired bi-frequency maps undergo several pre-processing stages for extracting features that can be used for fault identification and classification.

The paper is structured as follows: after the introduction, the experiment is described and the most problematic aspects of the data processing are indicated. After that, the key aspects of the processing methods are described in theory. Finally, the results are presented with an indication of all intermediate steps and the conclusions are formed.

2 Methodology

The aim of this section is to describe the key elements of the methodology. A summarized flowchart of the proposed procedure is presented in Fig 1.

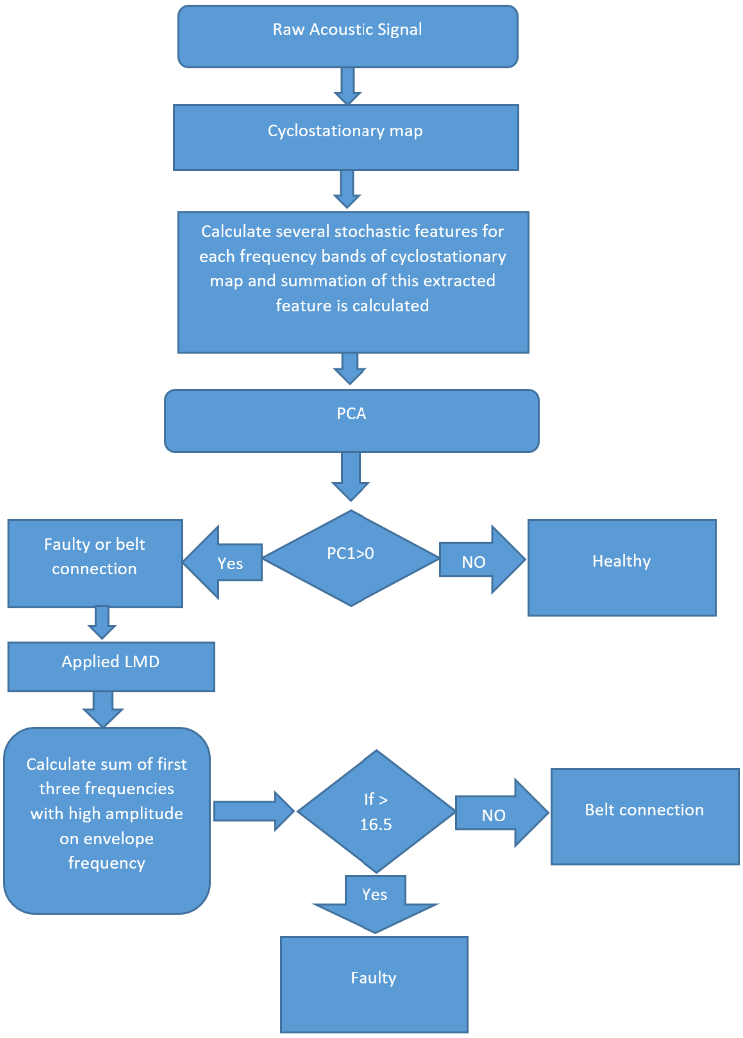


Figure 1: Flowchart of the proposed procedure

Firstly the captured raw acoustic signals by the mobile robot are loaded. Cyclostationary is a beneficial method for fault identification in industrial rotating machineries. The cyclic modulations in captured acoustic signa can be determined via analysis of a bi-frequency map called Cyclic Spectral Coherence (CSC). Therefore, In order to analyze, the complex acoustic signal cyclostationary approach is applied for accurate detection of faults and bi-frequency map are computed for each samples see Fig. 2. In this figure the Cyclic Spectral Coherence (CSC) is plotted for three different cases.

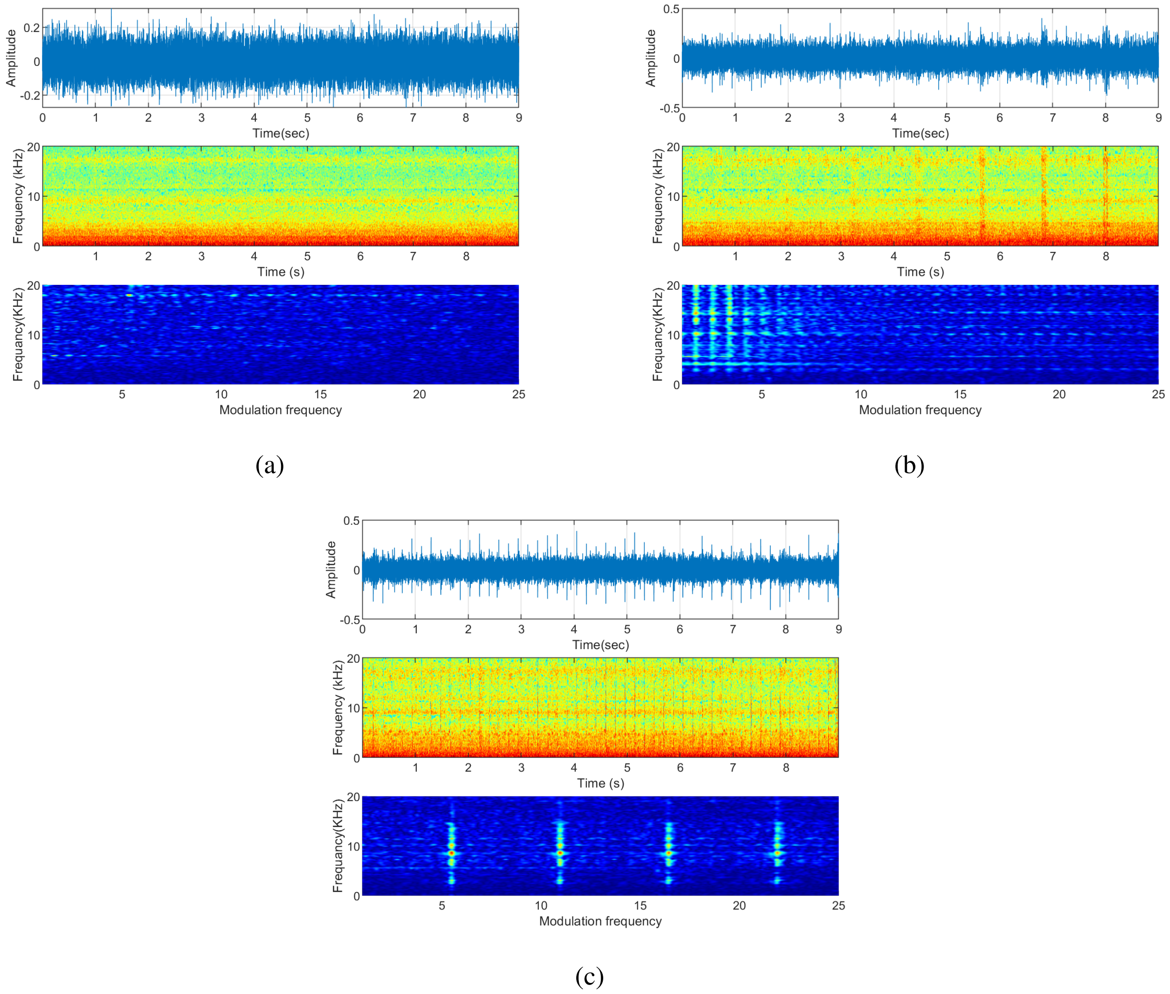


Figure 2: Raw, spectrogram, andCyclic Spectral Coherence (CSC) for three diffrent cases (a).Healthy cases (b) Belt connection cases (c) Fault cases

Afterward, several stochastic features including signal-to-noise ratio (SNR), spectrum (SNR), and peak frequency level were calculated for each frequency band of extracted bi-frequency maps, and a summation of extracted features are calculated. Feature dimension reduction is an important step in the processing of acoustic signals. The demission reduction techniques help to avoid challenges due to computational cost and complexity of the ensuing classification task. To this end, principal component analysis (PCA) was used for reducing the dimensionality of the extruded features [26].

Afterward, several stochastic features see Fig. 3, were calculated for each frequency band of extracted bi-frequency maps, and a summation of extracted features are calculated. Feature dimension reduction is an essential step in the processing of acoustic signals. The demission reduction techniques help avoid challenges due to computational cost and complexity of the following classification task. To this end, principal component analysis (PCA) was used to reduce the dimensionality of the extruded features [26]. In the next step, the PC1 is selected as the main feature for following procedure based on the fact that PC1 has more information in comparison to PCA components. In this step, by using the PC1, the idlers can be categorized into two main groups namely: healthy cases and faulty cases include belt connections cases. It should be noted that the belt surface is never a single consistent loop. Therefore, It should be manufactured as a linear strip, which is then installed as a loop by making a connection between ends. In some cases, the source of non-cyclic impulses that are not related to faulty idlers are intense noises produced by a metal joint connecting two pieces of the belt. The moving metal joint is heating the idlers and producing much stronger noises than a typical interaction between the belt and idlers. Due to this fact, actual faulty signatures usually appear on coefficients of idler speed, while other harmonic patterns related to metal join occur on the low-frequency band; In this step the frequency features were used to separate faulty and joint belt cases. However, in a real mining environment, many noise sources affect acoustic signals and cause the inefficiency of frequency methods. To address this issue, the local mode decomposition (LMD) is used to denoising the signal before extracting frequency features. Later, the envelope analysis is applied to the rest of the cases that filter by LMD. Finally, the sum of the first three frequencies with high amplitude on envelope frequency is calculated to separate real faulty cases from other cases.

mean	max	root mean square	Standard division	variance	skewness	kurtosis	Shape factor
Impulse factor	Crest factor	moment 3	moment 4	moment 5	moment 6	energy	median

Figure 3: Features

3 Results

In this section, the proposed methodology is applied to a real acoustic dataset that is acquired in a mining site. The dataset includes 135 samples of the acoustic signal from idlers of conveyer belts recorded by a robot with a sampling rate 44.1 KHz and 16-bit resolution using the cardioid microphone.

In the first part, the cyclostationary maps were calculated for all cases and mentioned features were extracted. Afterward, the PCA is applied to all the extracted features. Fig. 4 presents the PCA components scores. As expected, most signal information is contained in PC1.

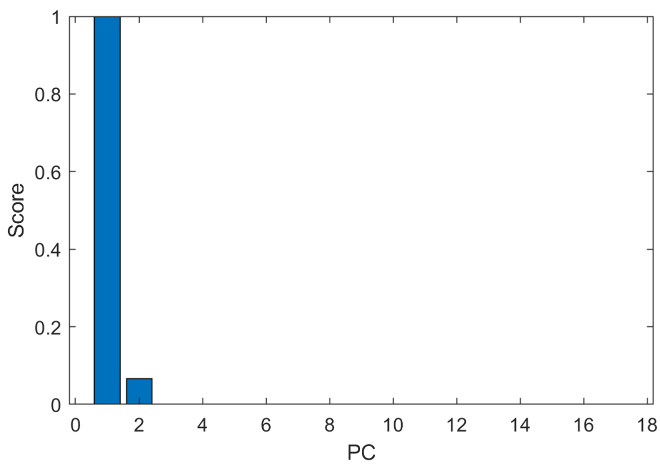


Figure 4: PC score

The PC1 value are plotted in 5 for all cases. As we can see, it can be divided into two different groups. First are the cases with a negative PC1 that are referred to as healthy cases, and the rest that have a non-negative value are referred to faulty candidates.

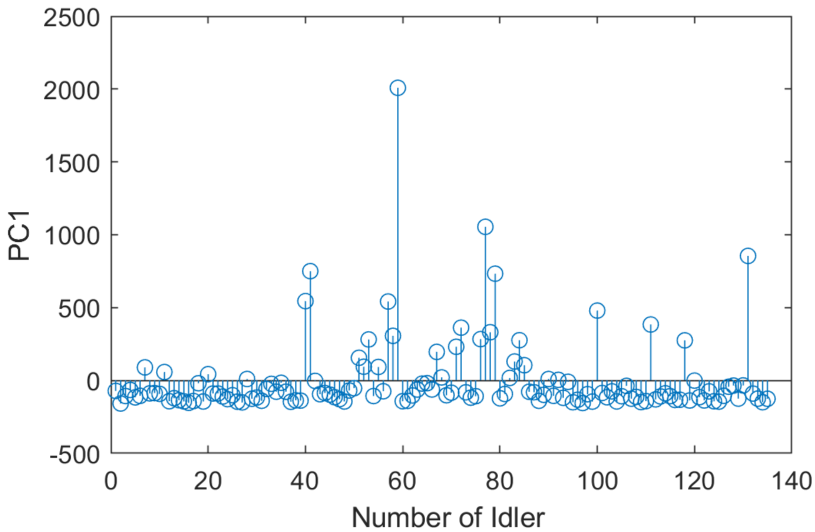
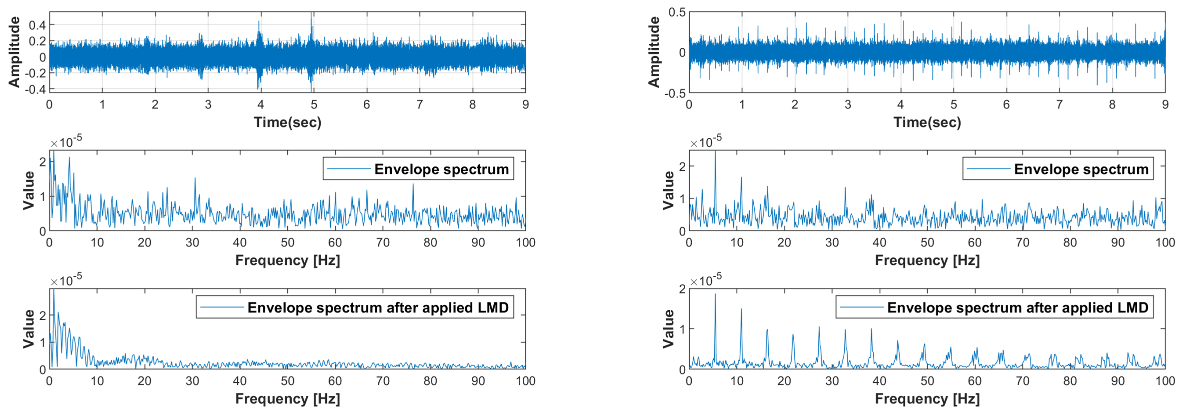


Figure 5: PC1 for all idlers

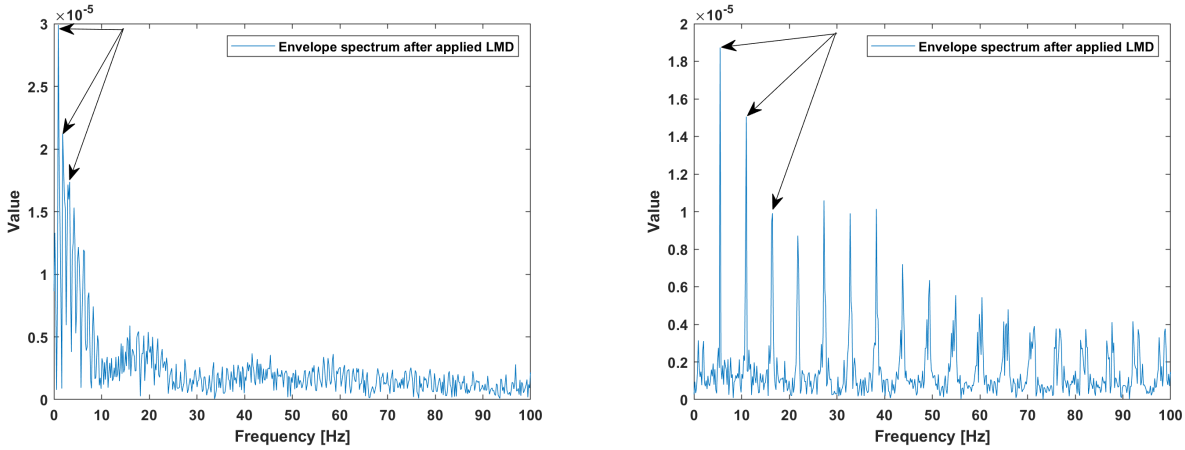
Fig. 6 is illustrated as a result of applied LMD to the faulty case candidate. As we can see in both cases, panel a (belt connection) and panel b (faulty) the quality of the spectrum envelope were not in good quality which increase the difficulty of extracting the valuable features. In contrast, after applying LMD, which works as a high pass frequency, the quality of the envelope spectrum is increased for the following process.



(a) (b)

Figure 6: Envelope spectrum of raw and filtered signal for two different cases (a) belt connection (b) Fault cases

Fig. 7 is shown, the envelope spectrum of belt connection cases panel (a) and faulty cases panel (b). As it can be seen, the most harmonic pattern for faulty cases has appeared on the coefficient of basic idler rotation speed (5.5 Hz). In contrast, the belt connection harmonic signature has appeared on the low-frequency band.



(a) (b)

Figure 7: Envelope spectrum after appling LMD with indication of harmonics (a) Belt cases (b) Fault cases

The summation of the first three frequencies with high amplitude on envelope frequency for each cases are plotted in 8. The faulty and belt cases can be separated by defining a threshold equal to three times the basic idler rotation speed.

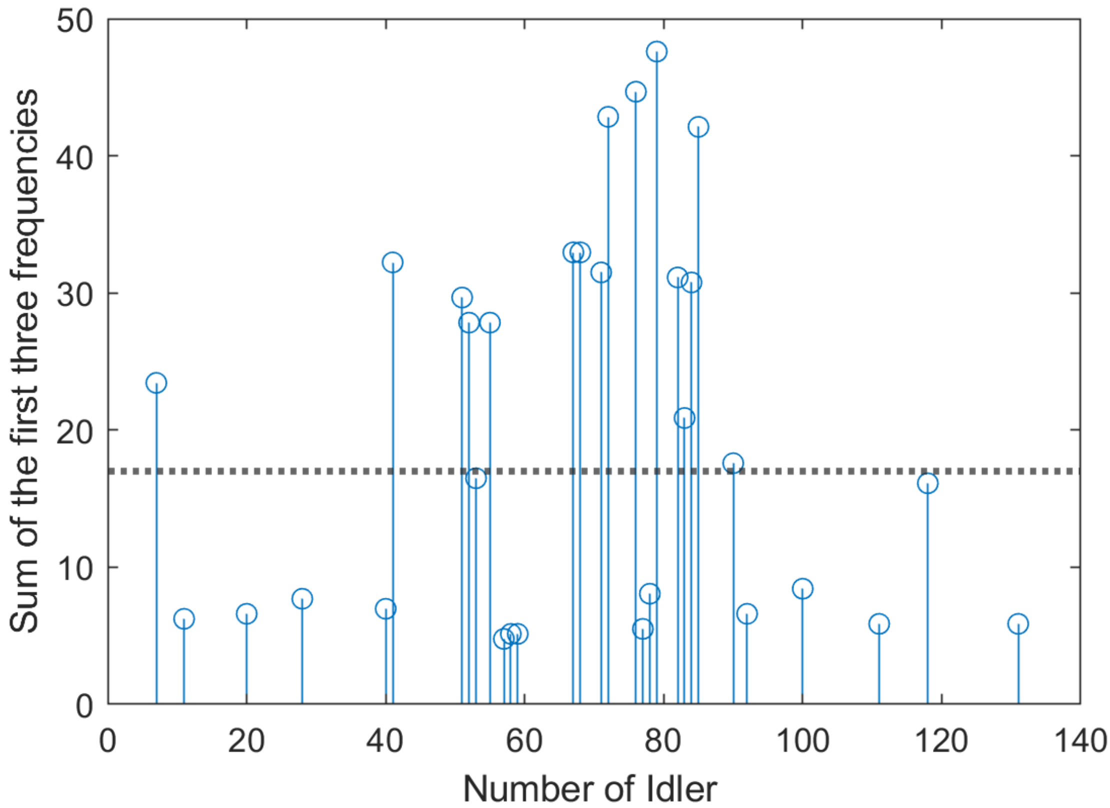


Figure 8: Separation of fault and Belt

The final results of the proposed methodology for all idlers are illustrated in Fig. 9.

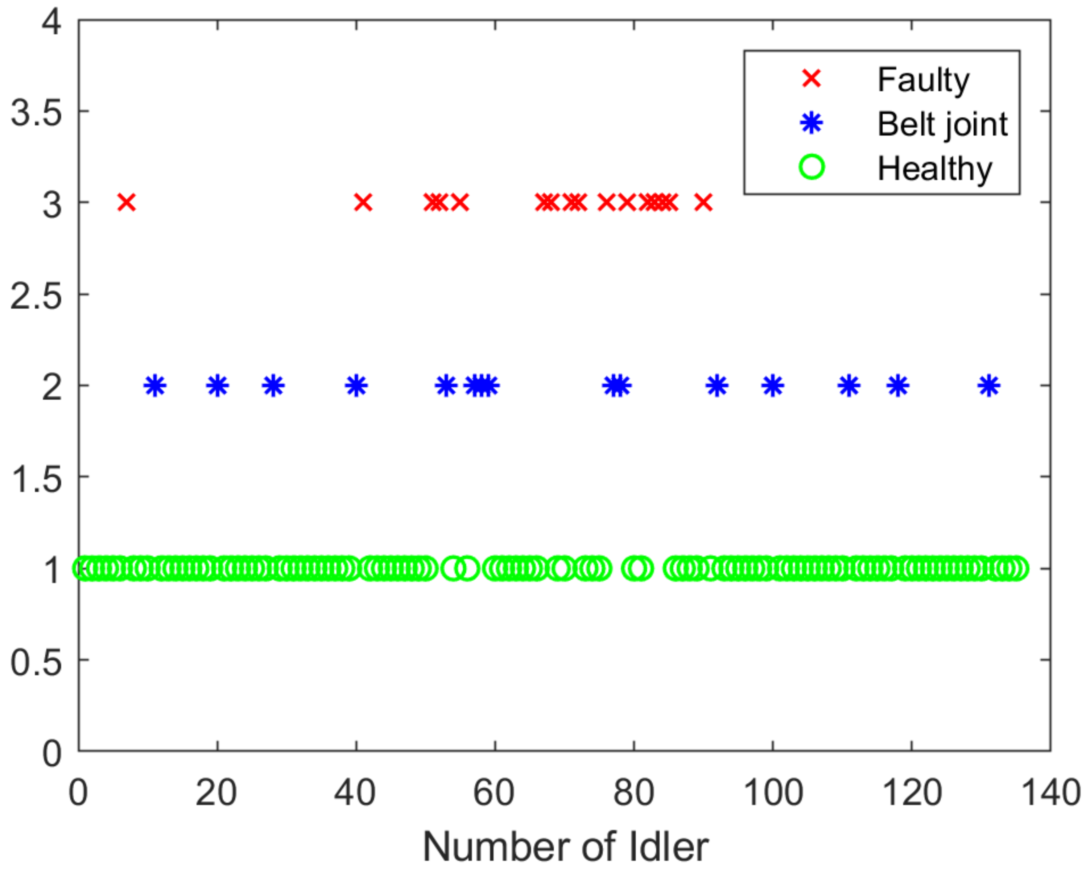


Figure 9: Final Result

4 Conclusions

In this paper, the authors present a very promising method for the classification of acoustic signals for the identification of damages in belt conveyor idlers. Based on the audio recording acquired by the mobile inspection robot, several classes of signals were classified by the proposed procedure. According to expectations, most of the idlers exhibited good technical condition. For the total number of 135 idlers, 16 of them have been classified as faulty, and another 15 idlers contained the signature of a belt joint passing over them, which may require posterior investigation by the expert, because they can belong to a class of good or bad technical condition. That leaves the rest of 104 idlers classified as being in good technical condition. In the further work, authors plan to extend the methodology to properly re-classify "belt joint" class so that all of the idlers can be included in one of two classes describing good or bad technical condition.

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