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FACULTY OF ELECTRICAL ENGINEERING

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UNIVERSITY „GOCE DELCHEV" - SHTIP
FACULTY OF ELECTRICAL ENGINEERING

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PREFACE

The Faculty of Electrical Engineering at University Goce Delcev (UGD), has organized the International Conference ***Electrical Engineering, Informatics, Machinery and Automation - Technical Sciences applied in Economy, Education and Industry-ETIMA.***

ETIMA has a goal to gather the scientists, professors, experts and professionals from the field of technical sciences in one place as a forum for exchange of ideas, to strengthen the multidisciplinary research and cooperation and to promote the achievements of technology and its impact on every aspect of living. We hope that this conference will continue to be a venue for presenting the latest research results and developments on the field of technology.

Conference ETIMA was held as online conference where contributed more than sixty colleagues, from six different countries with forty papers.

We would like to express our gratitude to all the colleagues, who contributed to the success of ETIMA’21 by presenting the results of their current research activities and by launching the new ideas through many fruitful discussions.

We invite you and your colleagues also to attend ETIMA Conference in the future. One should believe that next time we will have opportunity to meet each other and exchange ideas, scientific knowledge and useful information in direct contact, as well as to enjoy the social events together.

The Organizing Committee of the Conference

ПРЕДГОВОР

Меѓународната конференција ***Електротехника, Технологија, Информатика, Машинство и Автоматика-технички науки во служба на економија, образование и индустрија-ЕТИМА*** е организирана од страна на Електротехничкиот факултет при Универзитетот Гоце Делчев.

ЕТИМА има за цел да ги собере на едно место научниците, професорите, експертите и професионалците од полето на техничките науки и да претставува форум за размена на идеи, да го зајканува мултидисциплинарното истражување и соработка и да ги промовира технолошките достигнувања и нивното влијание врз секој аспект од живеењето. Се надеваме дека оваа конференција ќе продолжи да биде настан на кој ќе се презентираат најновите резултати од истражувањата и развојот на полето на технологијата.

Конференцијата ЕТИМА се одржа online и на неа дадоа свој допринос повеќе од шеесет автори од шест различни земји со четириесет труда.

Сакаме да ја искажеме нашата благодарност до сите колеги кои допринесоа за успехот на ЕТИМА’21 со презентирање на резултати од нивните тековни истражувања и со лансирање на нови идеи преку многу плодни дискусии.

Ве поканувааме Вие и Вашите колеги да земете учество на ЕТИМА и во иднина. Веруваме дека следниот пат ќе имаме можност да се сретнеме, да размениме идеи, знаење и корисни информации во директен контакт, но исто така да уживаме заедно и во друштвените настани.

Организационен одбор на конференцијата

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ACOUSTIC SIGNAL DENOISING BASED ON ROBUST PRINCIPAL COMPONENT ANALYSIS

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Abstract

Robust principal component analysis (RPCA) is a powerful procedure which decomposes a matrix into its low-rank and sparse matrix components. As such it can be used for signal denoising in situations where useful part of the signal can be represented as a low-rank matrix, which is usually the case in acoustic signals with some inherent periodicity. This paper examines the applicability of RPCA for cyclostationary acoustic signal denoising by decomposing the Short-time Fourier transform of a signal and eliminating its sparse component. The main purpose of this approach is improvement of the signal-to-noise ratio in acoustic signals obtained in noisy industrial surroundings for the purpose of fault detection or machine state estimation. The procedure is tested on artificially generated signals as well as on real acoustic recordings.

Key words
Acoustic signals, Noise removal, RPCA, Industrial state estimation.

Introduction

With the rise of accessibility of smart hardware devices and inexpensive sensors, acoustic signals are starting to be used for the purposes previously reserved for some other, highly specialized, sensor systems. From ambient event detection, classification of movement, musical instrument detection, all the way to industrial predictive maintenance and state estimation, sound has become a medium which is capable of absorbing various information quite efficiently. It has been long known in the literature [1] that sound can be used to detect fault in rotating actuators sometimes faster than vibration signals which have been traditionally used for solving this issue. The problem, however, lies in the same feature of acoustic signal which makes it so attractive for diverse application: sound is capable of detecting even the slightest changes in the environment, which makes it prone to severe noise contamination. This is especially true in real industrial settings which are generally very noisy and which consist of large amounts of machines working simultaneously. With this in mind, identifying a single actuator in an industrial plant and performing sound analysis for that particular machine is more than challenging.

One of the popular algorithms in the last decade which has been used on acoustic signals, usually for the purpose of vocal extraction, is Robust Principal Component Analysis (RPCA). It is an extension of a widely used statistical data analysis tool called Principal Component Analysis (PCA) and is used to decompose any matrix into its low rank and sparse matrix components. This has proven to be very useful for diverse applications such as background removal from video surveillance cameras, instrument extraction and vocal extraction from musical compositions, etc. One example of musical application is given in [2] where Short Time Fourier Transform (STFT) of the musical composition is observed and it is concluded that musical instruments have a repetitive appearance on the time-frequency plot, which should correspond to the low rank matrix presentation, while vocal segments are chaotically scattered in time and frequency, corresponding to the sparse matrix. Even though authors have not yet seen the application of RPCA decomposition for preprocessing of acoustic signals obtained from industrial surroundings, arguments for its potential use in this area are quite compelling. Bearing in mind the successful application of RPCA approach on music signals, we can analogously conclude that the expected behavior of rotary actuator signals in time-frequency domain can correspond to a low rank matrix (due to its cyclostationary behavior which leads to discrete number of peaks in the frequency domain), and the surrounding noise is expect to behave as a sparse matrix, similarly to vocal components in music.

The main idea of this paper is to test the aforementioned assumption: that RPCA decomposition of acoustic signal of a rotary actuator made in noisy industrial surroundings will yield a low rank matrix corresponding to the sound of the actuator and sparse matrix corresponding to the unwanted noise. This will be done on artificially generated signals first. These signals will be created to have similar properties as real signals from rotary actuators, with added noise, so that signal-to-noise ratio (SNR) can be controlled. After that the algorithm will be tested on real signals in three scenarios: 1) when the background noise is stationary, which is the most common case, and the source of the background noise are just the sounds of other machines in the plant; 2) when impulse disturbance is added to the background noise in a form of the hammer hitting the metal surface periodically; and 3) when speech contamination is present, i.e. people are speaking near the microphone which records the sound of the actuator. Since the nominal sound of the actuator is unknown, SNR cannot be measured for the real industrial scenario, so the performance of the algorithm will be assessed by analyzing the time-frequency representation of the filtered signal and by listening to the obtained recordings.

This paper is structured as follows. In Section 1 a short literature review is presented which introduces the way RPCA algorithm is used in the literature and the use of acoustic signals for predictive maintenance in real industrial surroundings. The RPCA based noise reduction algorithm is presented in Section 3, while the specific rotary fan mill on which the test has been done is described in Section 4. Results both on artificial and real signals are given in Section 5, while the conclusion of the paper is given in the last section.

1. Literature review

The initial attempt to robustify the PCA method, which is severely influenced by intensive noise, dates back to 1970s and 80s [3]; however, due to inability to implement it in polynomial time and the fact that there were no performance guarantees, the approach has not been popular until around 2010. During that time idealized version of that problem has been examined by [4] and has shown promising results. From then onward applications of RPCA methods have been diverse, from image processing applications such as background removal or recovery in video surveillance [5], to cyber security [6]. The application most interesting in the light of this paper is the use of RPCA for acoustic signals. By far the most popular subject in this area has been instrument and singing voice separation from musical compositions. This application has shown great potential, starting with a simple masking procedure in time-frequency domain, proposed by [2], this simple algorithm has been adopted and upgraded by using repeating pattern extraction [7]. There was even an attempt to implement this procedure in real time using bilateral random projection to reduce the amount of necessary computing [8]. It is evident that the applicability of RPCA approach is vast, and new practical applications are emerging every day.

This paper is concentrated on the problem of separating useful sound of the rotary actuator from the surrounding noise in acoustic signals recorded in industrial surroundings, and as such, this issue is quite similar to separation of vocal component from instruments, as proposed by [2]. Even though it has been long shown that acoustic signature of rotary actuators is cyclostationary and that sound can be used for state estimation [1] the authors are yet to see the RPCA factorization used for such purposes in the literature. For that reason, the aim of this paper is to test the assumption that RPCA factorization can be used for preprocessing of acoustic signals for the use for state estimation algorithms such as the one proposed in [9].

2. RPCA based noise removal

Robust principal component analysis is a modification of one of the most widely used statistical algorithms for data analysis – PCA. The goal of RPCA is to recover low rank and sparse components of severely corrupted matrix M. Procedure itself, as stated in [4] is defined as an optimization problem:

$$\begin{array}{ll} \text{minimize} & \|L\|_* + \lambda\|S\|_1 \\ \text{subject to} & L + S = M \end{array}. \qquad (1)$$

Here, $L \in \mathbb{R}^{n\times m}$ represents a low rank component of matrix $M \in \mathbb{R}^{n\times m}$, and $S \in \mathbb{R}^{n\times m}$ represents its sparse component. Nuclear form of the matrix (sum of all singular values) is denoted as $\|\cdot\|_*$ and the L1-norm of the matrix is denoted as $\|\cdot\|_1$. The parameter λ is used to balance between the rank of L and sparsity of S. A good choice of that parameter is offered in [4] as $\lambda = 1/\sqrt{\max(n,m)}$ and this value has been used in this paper as well.

Bearing in mind the problem we are aiming to solve, i.e. denoising acoustic signals obtained in industrial surroundings, we should examine what kind of behavior is expected in a signal. First of all, the recorded signals are obtained with the goal of state detection of rotary actuators. That means that the acoustic signal is expected to have cyclostationary signature [1] with dominant frequency components related to rotating frequency and its higher harmonics. By observing the STFT of the signal it is expected to contain several peaks in frequency domain which corresponds to straight lines parallel to time-axis in time-frequency presentation, i.e. the STFT matrix is expected to have low rank. Intense surrounding noise, however, is expected to exist on all the frequencies and should have the behavior which corresponds to sparse matrix in time-frequency domain. As such, the STFT of acoustic signal can be decomposed into informative cyclostationary component, L, and noise which is expected to be contained in the matrix S from Eq. (1).

The algorithm which will be used for testing this hypothesis will be a modified version of the work proposed in [2] for separation of vocal components from musical compositions. Here vocal components have similar attributes as the surrounding noise, while musical instruments have the behavior which is expected in rotary actuators. The procedure consists of five steps:

1) Separating recorded acoustic signal into smaller frames 10 s long
2) Calculating matrix M which is a STFT of a frame (using Hamming window 1024 samples long, with 1000 samples overlap)
3) Using RPCA to decompose STFT into low rank matrix L and sparse matrix S
4) Depending on the type of algorithm which will be implemented in this step one of two actions can be taken
    a. Denoising without a mask: matrix L is adopted as the filtered signal, $M_{filtered} = L$;
    b. Denoising with a mask: masking is performed to obtain the filtered signal, $M_{filtered}$ from the original matrix M;

5) Inverse STFT of $M_{filtered}$ is obtained as a reconstructed filtered signal in time-domain

Masking procedure in step 4) b. has been proposed by [2] to improve the separation results. The masking is used to indicate which part of the original matrix M is useful and should be kept in filtered signal. Binary time-frequency mask is obtained as

$$B(i,j) = \begin{cases} 1, & |L(i,j)| > k \cdot |S(i,j)| \\ 0, & \text{otherwise} \end{cases}, \quad (2)$$

for all $1 \leq i \leq n$ and $1 \leq j \leq m$. Parameter k has been set to the value of 0.3, which is the value that yields best signal-to-noise (SNR) ratio for artificially generated signals. After calculating this mask, the filtered signal STFT is determined as

$$M_{filtered}(i,j) = B(i,j)M(i,j). \quad (3)$$

3. Case study

Acoustic signal denoising algorithm presented in the previous chapter has been created for the purpose of noise removal in industrial surroundings, and as such it will be tested both on artificially generated signals and on real acoustic recordings. The problem which we aim to tackle in this paper is related to predictive maintenance of coal grinding fan mill in thermal power plant Kostolac A1 in Serbia.

The main purpose of coal grinding subsystem is to pulverize coal into fine powder so that it can be transferred to the boiler where it is used as a fuel. The grinding process is achieved with fan mills which have an impeller within them with 10 impact plates placed around the center in circular fashion. Mill is filled with coal as the impact plates rotate with the speed of around 12.5Hz, and the friction between chunks of coal and the plates pulverizes the coal. Unfortunately, one side effect of this process is that the impact plates themselves get worn as the number of working hours increases. While they become depleted their performance and efficiency suffer and if the maintenance is not conducted on time this can lead to failures and shutdowns of the entire subsystem. For that reason periodical maintenance of the mills is usually conducted and recently there is an attempt to automate the process using acoustical recording obtained in the vicinity of the mill [9].

Acoustic signals are recorded by placing the microphone near the mill. The sampling frequency is 48kHz and is later downsampled to 4.8kHz due to the fact that the most important frequency components are lower than 2000Hz. It is shown that acoustic signals are informative enough to detect whether the impact plates are functioning properly or the maintenance needs to be conducted [9]; however, any unexpected noise in the acoustic recording can severely influence any similar state detection algorithm [10]. For rotary actuators such as fan mills, the acoustic signature is quite predictable in the frequency domain. There are dominant peaks at characteristic frequencies and several higher harmonics are usually visible as well. In the case of fan mill in thermal power plant Kostolac A1 in Serbia, the frequency signature is shown in Fig 1. (left). The dominant peak is at the rotating frequency of $f_r = 12.5$Hz and its higher harmonics, as well as at the frequency at which the impact plate passes near the microphone (since there are 10 impact plates, that frequency is at $f_p = 125$ Hz) and its higher harmonics. STFT of the signal is typical for stationary behavior, i.e. there are dominant constant lines at specific frequencies. What is notable is that the signal shown in Fig. 1 (left) is naturally noisy due to the fact that even in nominal working conditions the real industrial surroundings is such that the acoustic noise is unavoidable.

Since real acoustic signals are naturally corrupted by noise, it is hard to experiment with them and to determine signal-to-noise ratio. For this reason artificial signal is generated which mimics the behavior of the real signal in frequency domain, but without the noise. The idea is not to model the signal exactly, just to mimic the shape in the frequency domain so that the RPCA based algorithm is similar and we can control and test for the signal-to-noise ratio. The proposed signal $x(t)$ is phase modulated so that the higher harmonics are generated in the frequency domain

$$x(t) = \sin(2\pi \cdot f_r t + \sin(2\pi \cdot f_r t)) + 3\sin\left(2\pi \cdot f_p t + \sin\left(2\pi \cdot f_p t\right)\right). \quad (4)$$

Frequency domain and STFT of the signal are shown in Fig 1. (right) and we can see that the behavior sufficiently coincides with the recorded one.

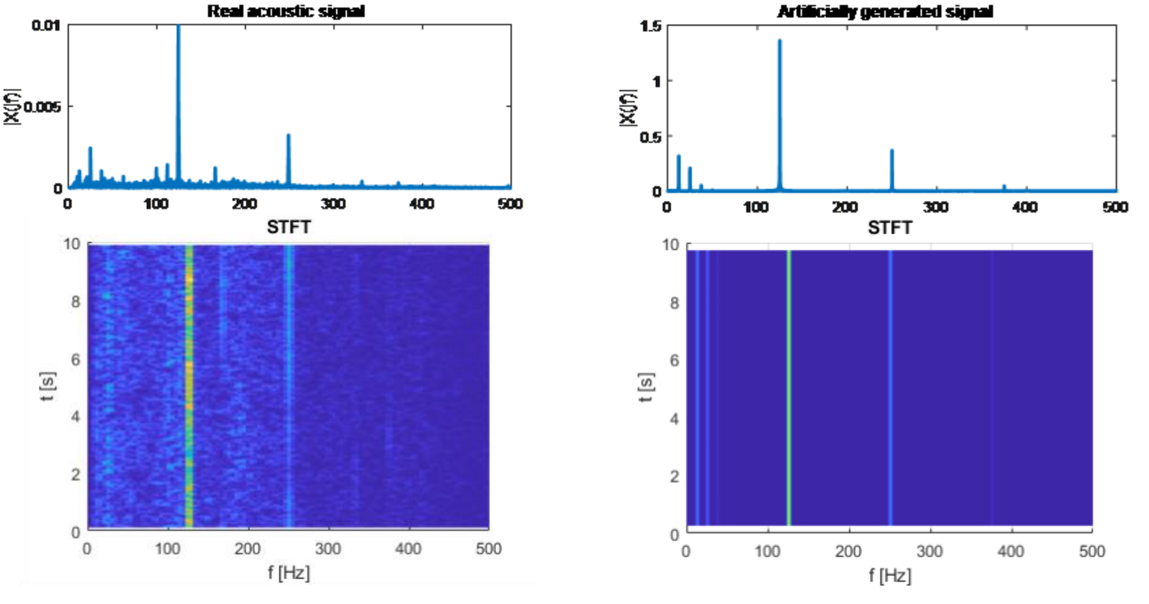

Fig. 1 Real signal recorded near the mill in frequency domain (upper left) and STFT (lower left), as well as the artificially generated signal in the frequency domain (upper right) and STFT (lower right).
Source: authors generated these images using Matlab.

4. Results

The aim of this paper is to examine whether RPCA noise reduction algorithm proposed in Section 2 can be used for noise removal of acoustic signals recorded in real industrial surroundings without significantly damaging the useful part of the signal. This was tested in two ways. First the artificial signal was corrupted with Gaussian noise and signal-to-noise ratios were measured before and after filtration to determine whether the proposed algorithm has any applicability. After that the real acoustic signals were used, and the algorithm was tested in three scenarios: 1) in nominal working conditions when stationary background noise is present; 2) when there is an impulse disturbance as sound of a hammer hitting a metallic surface; and 3) when there is noise from people talking near the microphone. While testing on real signals measuring signal-to-noise ratio is not possible, so the algorithm is tested by visual inspection of the behavior of signal in time-frequency domain as well as by listening to the resulting audio.

Artificially generated signal

Signal described in Eq. (4) was polluted with artificial Gaussian noise of different intensities, and the algorithm was tested with and without the application of mask. The results can be seen in Table 1 and shows a promising behavior of the RPCA method. First of all, in all instances denoising without the mask has shown better results than the one with mask, which is a compelling argument that while implementing this procedure on real signals the mask should not be used. Furthermore, when the signal-to-noise ratio is quite good (i.e. greater than 0dB) the algorithm does not enhance the quality of the signal significantly. Not only that, but when the noise is weak enough (SNR of 10 dB) this algorithm tends to corrupt the signal more than it enhances it. The true power of this procedure becomes evident when the noise is stronger than the signal, which is the case in the industrial surroundings. When SNR is lower than 0 dB this procedure significantly recovers the corrupted signal and furthermore the bigger the noise, the better relative increase in signal quality is achieved.

To visually inspect the performance of the algorithm it is informative to observe matrices S and L obtained with RPCA. In Fig. 2 it can be seen that the sparse matrix S has indeed gathered most of the noise, while in the low rank matrix L are all the dominant components of the original signal. It is evident as well that some components of the original signal are partly in matrix S as well (mainly those at the frequency of 125 Hz) and that is probably the reason why this procedure does not perform very well when the noise is negligible – the sparse component which is eliminated takes some useful information from the signal. Figure 3 shows the original, noisy and reconstructed signal in time domain.

Table 1 Signal-to-noise ratio before noise reduction, after noise reduction without a mask and after noise reduction with mask

SNR before denoising	10	5	0	-5	-10	-15	-20
SNR after denoising without mask	5.6	5.5	5.2	3.9	1.1	-3.7	-8.9
SNR after denoising with mask	4.2	3.2	0.4	-1.6	-5.8	-10.9	-15.7

Source: authors generated this data using Matlab.

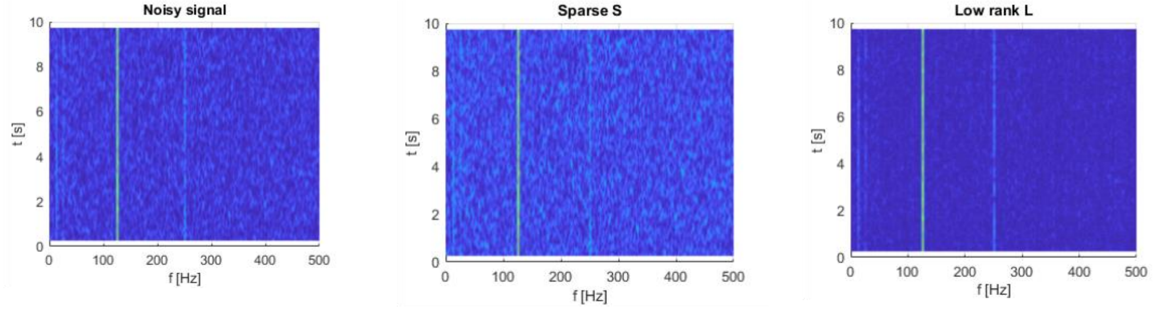

Fig. 2 STFT of artificially generated noisy signal for SNR value of -5dB (left), sparse matrix S (center) and low rank matrix L (right) obtained after RPCA decomposition.
Source: authors generated these images using Matlab.

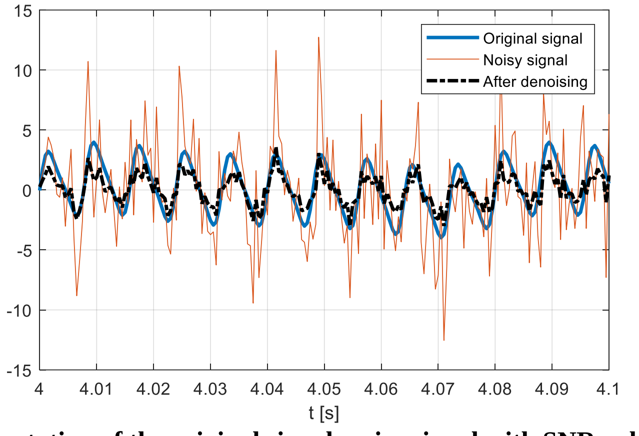

Fig. 3 time domain representation of the original signal, noisy signal with SNR value of -5dB and the signal obtained after denoising procedure without the mask.
Source: authors generated this image using Matlab.

<u>Real acoustic signals</u>

As noted from Fig. 1, the acoustic recordings obtained from the real industrial surroundings are naturally noisy and as such it is quite difficult to extract the useful signal from the noise. Applying the RPCA denoising procedure on such signal we get the similar results as with artificially generated ones. Figure 4 shows STFT of an original signal and low rank matrix *L* (which also represents reconstructed signal without mask). It is evident that low rank matrix has managed to extract all the dominant frequency components; however, some of the components on lower frequencies, which originally had lower amplitude, are missing. This is due to the fact that there is a more severe noise pollution on lower than on higher frequencies.

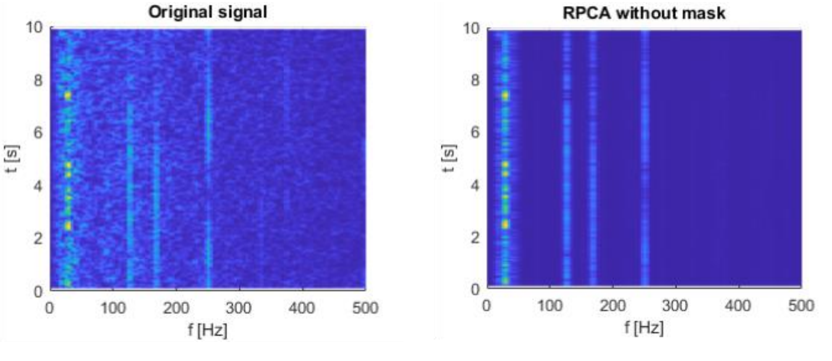

Fig. 4 STFT of real acoustic signal (left) and RPCA reconstruction (right).
Source: authors generated these images using Matlab.

These results indicate that RPCA method can remove nonstationary noise from loud industrial surroundings, while keeping stationary features of the signal (i.e. dominant frequency components). The next test is to check whether additional disrupting noise can be filtered out as well. As it is shown in [10] dominant noise such as impulse disturbance in time domain or added speech signal can significantly damage state detection algorithms. Figure 5 shows the behavior of this denoising procedure when loud impacts of hammer to metal can be distinctly heard on the recording. As can be seen, impulse disturbance in time domain is presented as dominant component on all frequencies, in the frequency domain. After RPCA procedure all of those nonstationary sounds are removed. Also, subjectively, while listening to the resulting sound signal, the impacts of hammer have indeed been eliminated and cannot be heard in the resulting recording. Final test is the signal corrupted with added speech. This problem is quite elusive due to the fact that speech signal changes in intensity in time, and dominant frequency components change as well. As shown in Fig. 6, RPCA denoising procedure manages to suppress this kind of contamination as well.

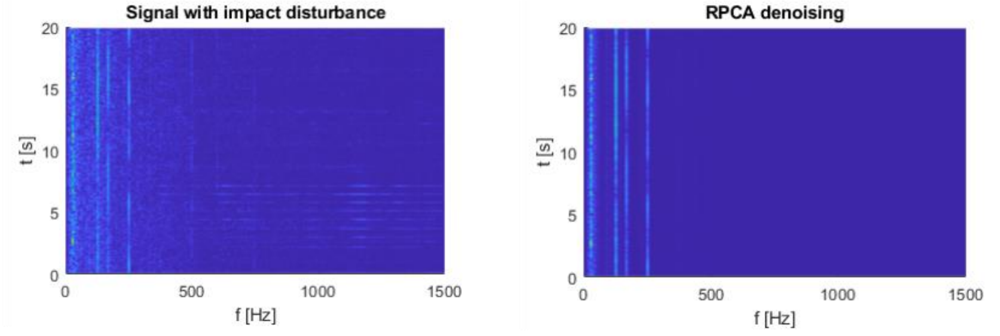

Fig. 5 STFT of acoustic signal with impulse disturbance (left) and RPCA reconstruction (right).
Source: authors generated these images using Matlab.

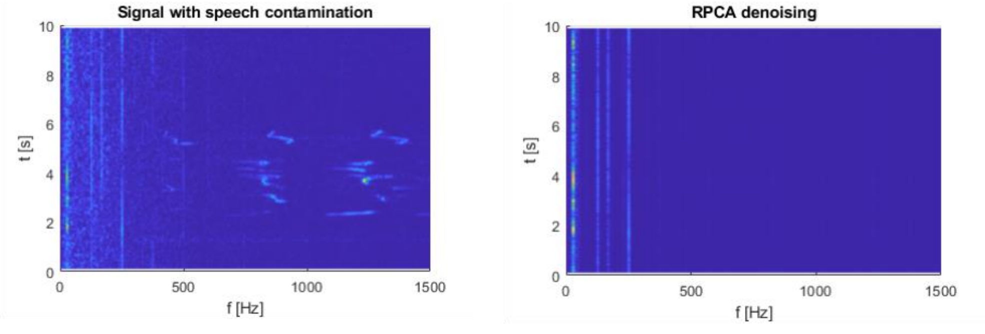

Fig. 6 STFT of acoustic signal with speech contamination (left) and RPCA reconstruction (right).
Source: authors generated these images using Matlab.

Conclusions

In this paper an RPCA denoising procedure has been proposed for the use on real acoustic signals obtained in industrial surroundings, as a preprocessing step for the purpose of state estimation. This algorithm has been tested on artificially generated signals, as well as on real acoustic recordings of a fan mill in thermal power plant Kostolac A1 in Serbia.

The results obtained on artificial signals seem promising. Since the signal is generated so that its behavior in time-frequency domain mimics the behavior of rotary actuator acoustic signature, results obtained here should indicate the applicability of this algorithm in real industrial surroundings. The noise used to pollute the signal is Gaussian, and signal-to-noise ratio was varied. The results show that the algorithm performs exceptionally well when the noise is severe; however it tends to degrade the useful signal if the noise is not significant (SNR larger than 5dB).

As far as the real recordings are concerned, subjective examination shows that all the added noise, in the form of speech contamination and impulse disturbance are eliminated effectively. What is not yet determined is whether the useful part of the signal is degraded using this procedure and whether that degradation (if any) influences the following steps of state estimation, which are the main reason for implementing this factorization.

Further work on this subject should aim to improve the quality of the algorithm. Since masking procedure is shown to be ineffective, some other approaches such as repeating pattern extraction could yield better results. On the other hand, real time implementation is something that can be useful in the industry, so improving the speed of the algorithm (which is currently far from real time) can be beneficial. Finally, a detailed analysis of the performance of state detection algorithms with and without the preprocessing step of RPCA factorization should be examined to verify the initial assumption that indeed the procedure removes mostly noise, and that the informative part of the signal is unscathed.

Acknowledgments

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