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Automatic segmentation of seismic signal with support of innovative filtering

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ABSTRACT

The paper presents a new algorithm for automatic segmentation of seismic signal. This segmentation relies on the observation of changes in the signal spectrum structure based exclusively on second-order signals statistics. The starting point of the proposed method are time-varying reflection coefficients of adaptive innovation filter. Schur's algorithm, performing the estimation of the reflection coefficients, is known as a fast, accurate and stable algorithm capable of quickly tracking the changes in signal statistics. Signal segmentation is a necessary stage for further processing of the signals, their interpretation, modelling or automatic classification. The issue of automatic segmentation is known in literature for its many applications (diagnostics of machinery, speech analysis, medicine etc.). There have also been a few proposals for segmentation of seismic signals. Unfortunately, segmentation of seismic signals is very difficult because of their variability. The purpose of the authors' work was to design an algorithm, which could be used in automatic processing of seismic signals in a deep underground copper mine. The paper presents the algorithm structure, defines its properties, specifies the values of parameters and presents the results of the effectiveness of the detection process. The obtained segmentation results are satisfactory.

1. Introduction

The appropriate processing and analysis of seismic signals might allow the extraction of knowledge about a seismic event. In practical mining applications, plenty of signals are acquired thanks to a number of sensors installed in the mine and a number of seismic events appearing every day. This has motivated the authors to develop an automatic procedure of seismic signal processing. Another important issue that emerged during manual analysis of seismic signals is the need for signal segmentation. Due to the used blasting technology in the considered mining company (or due to the ensuing aftershocks), it often happens that one observation (one signal) contains several impulses (shocks) related to a recorded seismic event. Some of them might be caused directly by an explosion at the mining face, while others might be an effect of stress release in the rock massive. Earlier works, for example by [1], have demonstrated that different sources generate signals with very different spectral content. This provides an opportunity to recognize events, but it also shows that several impulses in a signal cannot be analysed together and they should be isolated, i.e. the signal should be segmented and each shock should be analysed separately. The abovementioned issues have led the authors to develop an automatic segmentation procedure. In our application, classical detection techniques operating in time domain are ineffective (they will be used but only for preliminary rough segmentation). It might happen that the instantaneous energy of the signal will be at a similar level although its spectrum structure, due to the different origin of the event, will be different. In this report, the authors propose segmentation in frequency domain, assuming that autoregressive modelling is appropriate. We propose to exploit the fact that changes in signal spectrum will result in the model's coefficients (the reflection coefficients of adaptive innovation filter) variation over time. Schur's algorithm (used here), performing the estimation of reflection coefficients, is known as a fast, accurate and stable tool capable of quickly tracing changes in the statistics of second-order signals. The purpose of the authors' studies was to design a robust algorithm, which could be used in automatic processing of seismic signals recorded at a deep copper ore mine. The paper presents the structure of the algorithm, defines its properties, specifies the values of parameters, and presents the results of detection effectiveness. The segmentation procedure is a two-stage one. In the first stage, we apply a simple method based on the energy criterion (signal envelope) applied directly in the time domain for raw signal. This approach ensures "rough" segmentation, i.e. it allows differentiat-

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ing the segments in which the energy is close to zero (lack of signal) or exceeds an arbitrarily defined level (an event has been recorded). In the second stage, the proposed method for detailed identification is used, i.e. we check whether preliminary segmentation actually contains single events and whether these events have similar nature (in terms of their spectrum structure). The paper refers to segmentation seen as a division of signal into separate fragments differing in terms of their spectrum.

The issue of automatic segmentation is known in literature for its many applications. Depending on the application, segmentation can be carried out in various ways, i.e. with the use of various criteria and in various domains (in time domain, frequency domain etc.). Generally, the issue of automatic signal segmentation has been widely discussed in literature.[2–5] In addition, different application domains can be specified such as: diagnostic monitoring of objects and processes (including diagnostics of machinery),[6–10] experimental physics,[11] electromagnetic field analysis,[12] radon radiation in caves,[13] processing of biomedical signals (ECG),[14,15] speech analysis[16–20] and econometrics.[21] Also, several algorithms regarding seismic signal segmentation have been proposed. However, literature in this area is not very rich.[22–24] Recently published works,[25–31] confirm that it is still an important problem also for seismic signal analysis. Among others issues, the need for signal segmentation to isolate fore-, main- and after- shock events was clearly reported in Ref. 26, for the purpose of automatic identification of the nature of these events - in [1], and for distinguishing different seismic volcanic patterns - in Ref. 32. Significant development of signal segmentation methods has been also observed in applications related to automatic processing and the analysis and recognition of speech signals. This paper has been inspired by the abovementioned progress in speech signal analysis. This group of automatic segmentation methods contains algorithms, which are mostly based on statistical analysis of signals.[18,19,33,34] One of these papers[33] describes signal modelling using the autoregression (AR) process and the generalized likelihood ratio test (GLRT), which concerns changes in spectral density of signal power over the analysed time interval. In fact, this is a variant of Brandt's algorithm.[35] Except for the solutions presented in papers Refs. 33,34, the aforementioned algorithms are complex in terms of calculation. The present paper proposes a segmentation algorithm whose starting point are reflection coefficients calculated with the support of Schur's adaptive algorithm [36]. This algorithm demonstrates fast adaptation to varying signal, stability and robustness to interferences.[17,37,38] The time-varying parametric spectrum is calculated based on Schur's coefficients, and is subsequently converted into time-varying signals in subbands ultimately used for the determination of the GLRT test.

The paper is organized as follows: Section 2 provides a description of the proposed algorithm, an analysis of its properties, a general plan of the processing and detection of segment boundaries, and a description of the procedure of detecting inter-segment boundaries considering the properties of the seismic signal. Section 3 presents the values of the applied processing parameters and the results of automatic segmentation using the proposed algorithm obtained for synthetic signals and seismic data recorded in an underground copper ore mine. Finally, Section 4 contains the summary and the conclusions.

2. Description of proposed algorithm

2.1. Seismic signal model

Assuming the linearity of the system (rock mass) through which the seismic signals are propagated from the source of vibrations to the recording sensor, described by impulse response (IR) $\mathbf{h}_i(t)$ dependent on the location of the vibration source, the seismic signal $\mathbf{y}(t)$ recorded by the sensor, being the consequence of the occurrence of I seismic events represented by signals in sources $\mathbf{x}_i(t)$, is described by the following relation:

$$\mathbf{y}(t) = \sum_{i=1}^{I} \mathbf{x}_i(t)*\mathbf{h}_i(t) + \mathbf{n}(t) \tag{1}$$

where $\mathbf{n}(t)$ is a seismic noise and the values in bold are spatial values in the Cartesian coordinate system (x, y, z). All the values found in relation (1) are random time-varying values, although we assume that the system is time invariant for a specific event. The IR $\mathbf{h}_i(t)$ exerts an increasingly decisive impact on the given component of the signal $\mathbf{y}(t)$ along with the increase of the distance between the source and the sensor. Owing to factors like multipath propagation, every $\mathbf{h}_i(t)$ an be represented as the sum of elementary IRs:

$$\mathbf{h}_i(t) = \sum_{n_i} \mathbf{h}_{in}(t) \tag{2}$$

usually consisting of no more than a few components. With respect to seismic signals recorded at Polish copper mines, the following resonance model of an elementary IR can be adopted [39]:

$$\mathbf{h}_{in}(t) = \mathbf{A}_{in} 1(t - t_{in})(t - t_{in})\exp[-\gamma_{in}(t - t_{in})]\sin[2\pi f_{in}(t - t_{in})] \tag{3}$$

where $1(t)$ is a step function. Model (3) is described by 4 sets of parameters, where $\mathbf{A}_{in}$ is the multiplier, t_{in} is a delay in relation to the time in the source, γ_{in} describes the speed of damping the vibrations, while f_{in} is the frequency of resonance vibrations. Relation (3) describes a standard fourth order IR and can be considered as an AR system. The analysis of the recorded seismic signals and the model (1)–(3) demonstrates that a change in the nature of a seismic event (caving blasting, natural tremor in the roof, natural tremor in the floor or destruction of a pillar), registered at a close distance, will result in a change in the signal spectrum, because various mass sizes participate in these different events, signals are propagated along various paths and/or various source directivities occur. With respect to recording from longer distances, the path of wave propagation from the source to the recorder exerts a growing impact on the spectra of the recorded signals. Therefore a change in either $\mathbf{x}_i(t)$ or $\mathbf{h}_i(t)$ results in a change in the signal spectrum. As spectrum changes in seismic signals can be very rapid and short-lived, the analysis and classification of these signals requires a fast and stable spectrum estimation method such as one based on Schur's algorithm. In a further part of the paper the signal is not described in a spatial form, hence $y(t)$ will denote a single component of the observation.

2.2. Adaptive innovation filter

One possible signal modelling methods is based on using autoregression process for this purpose, i.e. describing the signal by means of prediction filter coefficients or reflection coefficients. The AR model is the adequate model for the analysed signals due to the resonance nature of signal propagation. Seismic signal is a non-stationary signal, though its local stationarity over a short period of time can be assumed by applying standardisation executed by Schur's algorithm. The adaptive orthogonal innovation filter, whose ladder structure is presented in Fig. 1, is used for signal analysis.[36]

The innovation filter consists of P sections. Each section is completely described with the use of time-varying Schur's coefficient $\rho(p, t)$: $p = 1, \ldots, P$. Samples of forward $e(p, t)$ and backward $r(p, t)$ prediction error signals make input for every section, while in the case of the first section, these are normalised signal samples. The adaptive

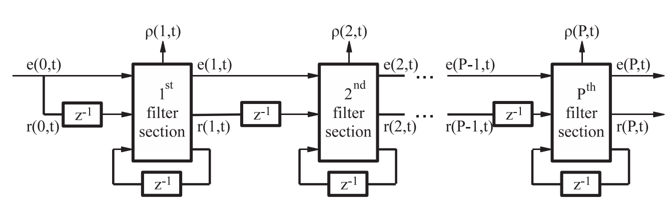

Fig. 1. The ladder-form realisation of the adaptive innovation filter.