Linear Prediction Coding in Verification of the Quality of Steel Anchor Adhesion in Rock Mass

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1. INTRODUCTION

In relation to the works conducted in mining that aim at a continuous improvement of the miners safety underground, there is a need for a method of determining the quality of fastening of steel anchors used in underground galleries. A steel anchor is placed in rock mass to strengthen the galleries constructions or as an indicatory anchor. The steel anchor is inserted in rock mass by means of glue. On many occasions the insertion fails to include the whole length of the glued surface. During exploitation the insertion channel of the anchor is subject to shifting because of rock mass leaps. In extreme cases the leap may result in cutting off the anchor. All damages have a significant effect on the strength of the gallery construction. The determining of the quality of anchor fastening is made more difficult by the fact that the method must be non-destructive and uninvasive while there is only access to the end protruding from the corridor wall.

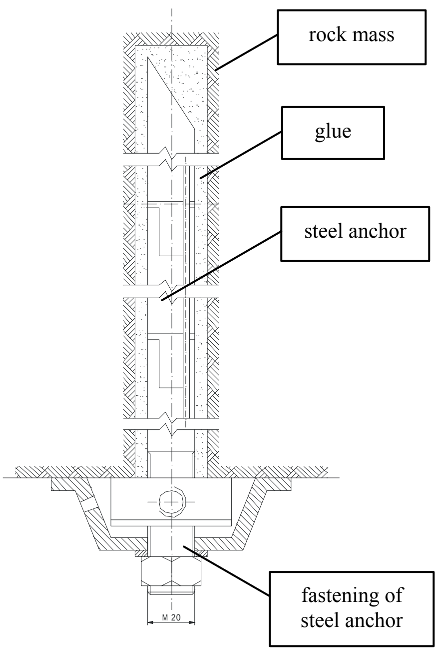

Figure 1 Steel anchor adhesion in rock mass

The paper presents a method of determining the quality of adhesion based on the analysis of the supersonic wave driven by the Dirac potential impulse. Analysis of the response signal by means of linear prediction coding assumes similarity between generating speech in the vocal tract of the larynx and generating the response of the steel anchor to Dirac impulse function. The model of the vocal tract used in the analysis of voiced sounds by LPC was used for the analysis of the response signal of the steel anchor driven by a train of impulses. The purpose of this research is the analysis of reflection coefficient and residue and their relations with physical parameters of anchor adhesion. Detection of clear interrelations between these two values will confirm the thesis that this method of signal analysis by means of LPC is useful in verification of the quality of steel anchor adhesion in rock mass.

2. THE LINEAR PREDICTIVE CODING METOD

The linear predictive method of speech analysis makes it possible to define the basic parameters of speech. The method is based on the assumption that a speech sample can be approximated as a linear combination of previous speech samples. The application of linear predictive analysis to estimate speech parameters is called linear predictive coding (LPC).

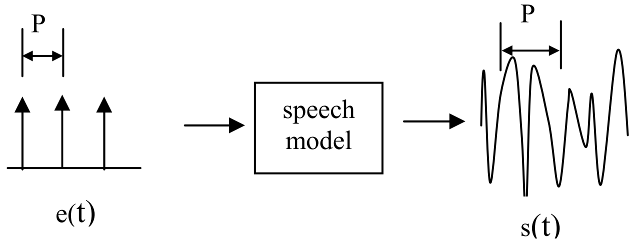

Figure 2 Model of the LPC method used for speech production

The model of the larynx is based on a time-varying digital filter that has coefficients representing the parameters of the larynx during speech. This filter is driven by a function e(t). In the case of voiced speech (sounds generated by the vibrating vocal cords), e(t) is a

train of impulses at the pitch (fundamental) frequency of vocal-cord vibration. In the case of unvoiced speech (sounds generated by the lips and tongue, there is no vocal-cord vibration), e(t) is random noise with a flat spectrum.
The method presented in the author's paper assumes similarity between the vibration of the vocal cords in the larynx and the vibration of the rod inserted in rock mass. Since it is possible to apply speech analysis to describe the larynx parameters during vocal-cord vibration by means of the digital filter coefficients, it is also possible to describe analogously the parameters of the medium in which the anchor vibrates. The LPC method consists in determining the parameters of this model in the form of the prediction coefficients and residual signals. It is possible to build the frequency response of the steel anchor model by means of resonance frequencies that are described by transmittance poles. The method of modeling systems with an all-pole transmittance is called linear prediction.
Knowing the impulse response of the model, let us determine its parameters. In order to determine the parameters of the model with an all-pole transmittance, we assume H(z) as the model transmittance:

$$H(z) = \frac{G}{1-\sum_{k=1}^{p} a_k z^{-k}}$$

where

G: the gain factor of the driving signal

ak: the coefficients of the prediction system

The linear response of the filter is the weighted sum of the previous P samples and at the moment n may be defined as:

$$s(n) = \sum_{k=l}^{p} a_k s(n-k) + G \cdot e(n)$$

The filter coefficients model the filter properties of the vocal tract. The values of the prediction coefficients are so determined as to minimize the average squared error by equating its first derivative to zero:

$$\frac{\partial E(e^2(n))}{\partial a_k} = \frac{\partial E(\hat{x}(n) - x(n))^2}{\partial a_k} = 0$$

where
E{}: the operation of calculating the average value

In order to find the prediction coefficients, the autocorrelation coefficients Φ_{ik} are determined:

$$\phi_{ik} = \sum_{n=1}^{N-1} v(n-1)v(n-k)$$

The method of autocorrelation (with a Hamming window) used for this purpose uses several periods of the larynx pitch in the case of speech analysis. In analyzing the signal from the anchor, the window was so selected as to include the time of a single response to impulse function. For a small required delay, the autocorrelation sequence of a segment of the speech signal multiplied by the window sequence approximates the autocorrelation sequence of the impulse response of the vocal tract. The Levinson-Durbin algorithm is used in solving the systems of equations. At each step after calculating the prediction coefficient of the known sample, the estimated value of the next sample is calculated. The estimated value is then compared to the actual value of the sample obtained from the signal.
The predictor transforms the uncorrelated input sequence e(n) into the correlated signal s(n). It is therefore possible to determine the transmittance path on the basis of the received signal only, when the excitation signal is not known exactly, so the influence of this transmittance on the original signal can be reduced. It is a substantial advantage of the method used for identifying the parameters of anchor insertion because the signal of impulse function may prove difficult to obtain in the conditions characteristic of a mine gallery.

3. THE OPTIMUM CHOICE OF THE PREDICTION ORDER AND LENGTH OF THE SIGNAL WINDOW

An important decision during the LPC modeling is the choice of the number of N samples from which speech parameters are calculated and the choice of the prediction order. The choice of the number of samples depends on the kind of the LPC analysis implemented, which may differ in the size of the signal frame and the order of the analysis filter. The number of prediction coefficients required for correct representation of the anchor response signal depends on the number of resonances and antiresonances in the spectrum. The prediction order should be twice as large as the time of propagating the wave from one, driven end of the anchor to the other end with the receiver. For a steel rod 1.2m in length tested at a laboratory, the time is 0.210 µs (it corresponds to fs ? 5 kHz). It was estimated that two poles per one kHz of the analyzed signal are sufficient for exact representation of the spectrum of the speech signal. Since the frequency of sampling must be twice as high as the maximum frequency of the analyzed signal, it is a good measure of the number of poles required for representing the speech signal. For example, for the sampling frequency of 10 kHz, the prediction order should be about 14.
The signal belongs to the class of locally stationary signals, for which sufficiently small windows of the signal are stationary, or they have permanent statistics of the second order. It is quite important because the LPC analysis presented above is based on the assumption that the signals are stationary.

4. DESCRIPTION OF THE MATLAB LPC MODEL

In this simulation, the signal samples are divided into frames of 0.25 s each, with an overlap of 50%. Each frame is analyzed by means of a Hamming window (Figure 3). Using the Levinson-Durbin algorithm, 11th order reflection coefficients are calculated from the autocorrelation coefficients. The original input signal is passed through an analysis filter (Figure 3). The residual signal is obtained at the output of the filter. The residual signal is then passed through a synthesis filter with the previously determined coefficients. The synthesis filter (Figure 3) is the inverse of the analysis filter.

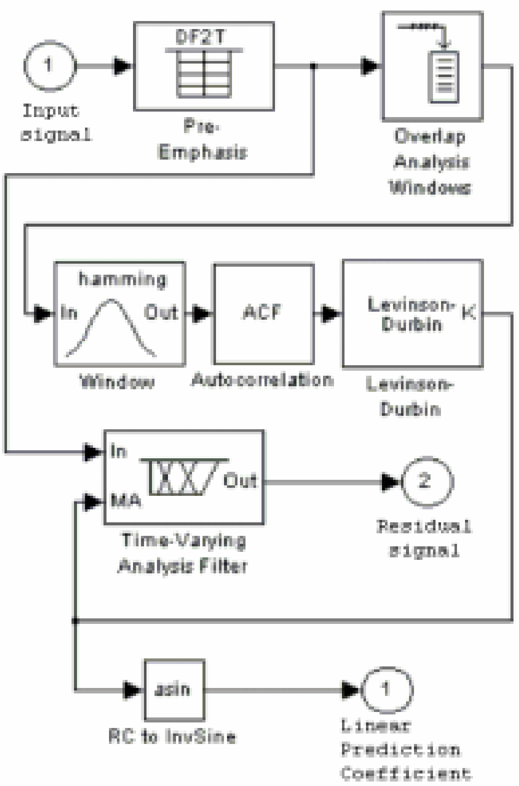

Figure 3 MATLAB - LPC analysis model

5. LABORATORY MEASUREMENT METHOD

In order to relate the parameters of the digital filter to the parameters of anchor fastening, a number of laboratory measurements were carried out. The tests involved a steel anchor 1.2m long fixed rigidly at three points. Two of them were fixed points at the anchor's ends while the third one remained mobile and was moved in the course of the measurements every 0.01m. As a result of driving the anchor by impulse function, a signal consisting of 120 replies was obtained. Thus, the characteristics of the input signal depending on the distance of the point of fixing were obtained. In order to prove the usefulness of the LPC method, the prediction coefficients should be related to the parameter of the point of fixing. In the process of coding, 10 separate prediction coefficients were obtained. The changes of these coefficients are illustrated in the graphs. (Figure 4). The X axis describes the distance of the third mobile point of fixing from one of the ends, the Y axis describes the value of the prediction coefficient. In order to obtain reliable results of the measurements, constant parameters of the model were assumed, such as the anchor length and diameter, the forces of anchor fixation, and the materials of all elements used during the measurements.

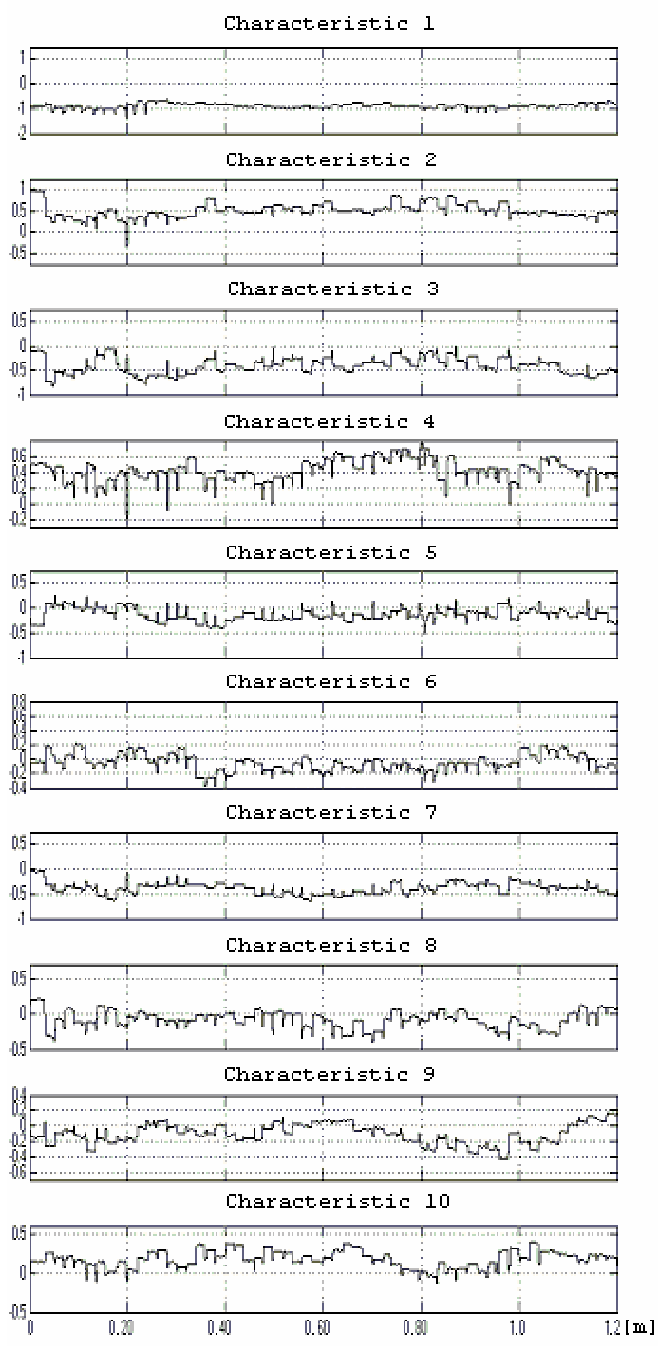

Figure 4 The characteristics of the prediction coefficient values depending on the distance of the third point of fixing from one of the anchor ends

6. CONCLUSIONS

Figure 4 illustrates the changes of 10 prediction coefficients depending on the distance of the third point of anchor fixation. On the basis of the analysis of the present characteristics, the following relations may be determined:

A) Change trend of prediction coefficient 4 (Characteristics 4, Figure 4) in the range from 0.4m to 0.8m is linearly dependent on the distance of the point of fixing.
B) Change trend of prediction coefficient 7 (Characteristics 7, Figure 4) is sinusoidal variable in the whole of the tested range.
C) All characteristics of the prediction coefficients show short-term trends linearly dependent on the position of the point of fixing.

Because none of the prediction coefficients remains linearly dependent in the whole of the tested range, unequivocal detection of the fixation point of the tested steel anchor is possible only when the range of the function arguments sought is limited.
On the basis of the prediction coefficients in the full range of arguments it is possible to determine a function that defines the probability that the tested steel anchor is fixed at a specific point. Using this function makes it possible to determine the point of anchor fixation with a specific uncertainty of such measurement. It is possible to determine the quality of steel anchor insertion in rock mass by means of the LPC using a comparative method. The results of the measurement are compared to the results obtained at the laboratory for various models of incomplete insertion.
The LPC method makes it possible to determine the point of discontinuity of steel anchor insertion in rock mass with a specific uncertainty.
The LPC method permits the identification of an incomplete insertion. The quality of such insertion may be determined through a percentage comparison of the prediction coefficients obtained from the measurement with the prediction coefficients determined at the laboratory for a model complete insertion.
It is possible to determine by means of experiment the relation between the above coefficient and the strength of the anchor construction in rock mass.
The aim of this research is to construct an integrated measuring system that will make it possible to detect the anchors whose damages affect negatively the strength parameters of the gallery construction.

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