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Constant Q Analysis by Optimized Sparse S-Transform

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SUMMARY

We improve the resolution of the entire time-frequency map of the S-transform by proposing a two-step sparsifying algorithm. First, we optimize the window widths for all time or frequency samples by using an energy concentration measure and then we sparsify the entire time-frequency map. The proposed method is applied on the seismic data for estimation of quality factor, Q . The results are compared with those of the standard S-transform. Our method outperformed the standard S-transform in estimating the correct value of Q .

Introduction

Analysis of the earth quality factor, Q , is a process to obtain the value of Q for the subsurface media from recorded seismic waves. Having the precise estimation of Q helps to compensate the energy absorption and wave amplitude attenuation due to anelasticity and inhomogeneity of the subsurface. Therefore, it can help to improve the resolution of seismic images. Time-frequency representations (TFRs) are common tools for estimating the value of Q (Wang 2004a). Obviously, an accurate TFR of the signal yields more precise estimation of Q . In this study we estimate Q by using a high resolution TFR. We improve the resolution of the standard S-transform (Stockwell et al. 1996) in a two-step sparsifying process. At first, the window widths used in the S-transform algorithm is optimized in an adaptive manner and by using an energy concentration measure (ECM). Then, in the second step, the prepared TFR is entered in the sparse time-frequency algorithm proposed by Gholami (2013) and therefore a well concentrated time- frequency map will be obtained. We use the final TFR for constant Q estimation. Application on synthetic and real data show high performance of the proposed method compared with that of the standard S-transform.

Method

The resolution of Fourier-based time-frequency representations depends on window widths used in their algorithms. The standard S-transform provides weak resolution at high frequency components because of inflexibility in the used windows. An approach to improve the resolution is using concentration measure of the energy in the entire time-frequency plane. To reach the goal, an optimization problem with a suitably defined objective function is required. The objective function should include a well-defined term which somehow provides a measure of energy concentration of its argument. Then the desired parameters can be obtained by optimizing the cost function over the domain of its definition. Mathematically, we define the window parameters as a solution of the following optimization problem:

$$\arg \max / \arg \min_{\text{window parameters}} \text{ECM}(\text{TFR}), \quad (1)$$

where TFR is the generated TF map by the S-transform for a given set of window widths. Obviously, the TFR is a function of window parameters. In (1), ECM is a function which measures the concentration of energy (Hurley and Rickard 2008). The optimization can be performed in non-parametric form as well. ECM and optimization is applied to the time distribution of each frequency component, separately. After we get the optimum S-transform TFR, we enter it to the algorithm of sparse time-frequency decomposition proposed by Gholami (2013). This work will produce a well sparsified map. Now we can use this sparse TFR for constant Q analysis proposed by Wang (2004a).

Application

For the constant Q analysis, we made a synthetic seismic signal. The seismic signal are composed of a random reflectivity series in random time instants convolved with a Ricker wavelet with dominant frequency of 35 Hz. Convolution process is done via non-stationary convolution model (Margrave 1998). Non-stationarity is applied to signal through using a constant Q factor with two various values of 50, and 80. Constant Q analysis procedure is shown in Figures 1 and 2 (see Wang (2004a) for more details about the Q analysis). As seen in these two figures, the TFR provided by the proposed method has higher resolution in comparison with the standard S-transform. Furthermore, the proposed method prevents the noises in the signal from transforming into the TF map. This issue makes the estimation of Q more accurate. The results of analysis for different values of Q are presented in Table 1. One can see from this Table that the performance of the proposed method is much better than that of the standard S-transform.

Figure 1 Constant Q estimation from spectral ratio of TFR. (a) synthetic seismic signal with $Q=80$, (b) standard S-transform TFR, (c) spectral ratio for standard S-transform TFR, (d) proposed method TFR and (e) spectral ratio for proposed method. Slope of the red line in (c) and (e) is $1/Q$. results of estimation are in Table 1. See Wang (2004a) for more details about theory of spectral ratio.

Table 1 Estimation of two different values of Q from TFR. Comparison of the results reveals the better performance of the proposed method.

Q	Estimated Q	
	standard S-transform	proposed method
50	61.3	55.1
80	90.3	84.7

Figure 2 Constant Q estimation. (a) real seismic signal, (b) standard S-transform TFR, (c) spectral ratio for standard S-transform TFR, (d) proposed method TFR and (e) spectral ratio for proposed method. Estimation of Q is 104.7 and 84.4 for (c) and (e), respectively.

Conclusions

In this article we proposed a new algorithm which sparsifies the time-frequency map of the S-transform in two steps. The first step is optimization of the window widths and the second is sparsifying the entire time-frequency map. It was seen that the time-frequency resolution is improved by our method, considerably. Application of the proposed method for constant Q analysis yielded acceptable results in comparison with the standard S-transform.

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