Efficient Implementation of FX-Cadzow Filtering at Different Stages of Seismic Data Processing

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Summary

FX Cadzow filtering is based on the concept of eigenimages filtering. The filter is applied at different stage of processing to enhance the signal to noise ratio. Present study demonstrates a cautious use of FX-Cadzow filtering on gathers and stacks showed improvement in the enhancing the data quality. The technique demonstrated in combination with other filters can be very useful to get rid of random as well as coherent noise.

Introduction

FX-Cadzow filtering is a form of eigenimage filtering. The eigenimage processing is brought to the industry and was applied on vertical seismic profiling data by Ulyrich, *et. al.*, (1988). From the time of its inception it was mostly restricted to T-X domain. However, as this method has evolved it is more frequently used in F-X domain. The method uses a noise suppression strategy based on matrix rank reduction.

Theory

The theory of eigenimage noise attenuation is also based separation between signal and noise similar to other noise attenuation scheme. In this case the concept of Singular Value Decomposition (SVD) is used, wherein the seismic data is composed of coherent and incoherent energies. The coherent energy can be separated from the incoherent energy, and there by suitably extracting some of the eigenimages. It is assumed that the coherent part of the energy is restricted to the first few eigenimages and thereby restricting our choice to a rank reduced matrix from which the coherent part of the energy can be separated.

From the theory of SVD a matrix $\boldsymbol{A}$ can be decomposed as

$$\boldsymbol{A}=\boldsymbol{U}\sum \boldsymbol{V}^{\boldsymbol{H}} \qquad \textbf{\textit{(1)}}$$

where **U, V** are the unitary matrices, and $\sum$ is the real diagonal matrix composed of the singular values of the σ_i 's such that $\sigma_1 \geq \sigma_2 \geq \sigma_3 \geq \ldots \geq \sigma_n$

From the above equation it follows that

$$A=\sum_{i}^{n} A_i \qquad \text{where} \qquad A_i=\sigma_i u_i v_i^{H} \qquad \textbf{\textit{(2)}}$$

$\boldsymbol{u_i}$ and $\boldsymbol{v_i}$ are the left and right eigen vectors.

On truncation, that is, restricting the summation till $\boldsymbol{k}$, where $\boldsymbol{k \leq n}$, the matrix $\boldsymbol{A}$ is rank reduced to $\boldsymbol{F_k(A)}$.

As $\boldsymbol{k}$ tends to $\boldsymbol{n}$, the closer we get to the true image. However, to recover the coherent part of the energy from a matrix $\boldsymbol{A}$ only first few eigenvalues are sufficient.

In the FX-Cadzow filtering, (Trickett 2002, 2003) problem is approached in a different way. Starting with the computation of DFT of the traces within a window (user-defined) and getting a Hankel matrix structure for each frequency slices and constructing a matrix $\boldsymbol{A}$ similar to equation (1) and then getting a rank-reduced form $\boldsymbol{F_k(A)}$ as explained.

The traces are recovered from elements of newly formed Hankel matrix $\boldsymbol{F_k(A)}$ by doing an inverse DFT over the new values. It is quite intuitive to know that most of the coherent energy is mapped into the first few eigenimages therefore a small value of $\boldsymbol{k}$ is sufficient to reconstruct the matrix $\boldsymbol{A}$ to an extent. In fact, it is also a proven result that if the noiseless data contains only $\boldsymbol{k}$ dips then choosing only $\boldsymbol{k}$ eigenimages with exactly reconstruct $\boldsymbol{A}$. This is sometimes known as the exactness property of the method.

In a peculiar seismic data, the coherent signal immersed in the embedded random noise can be extracted by reducing the number of k values, i.e., number of eigenimages. Larger the length of the filter (number of traces to construct the Hankel matrix), harsher is the impact.

The filter works very well for random noise attenuation however, care has to be taken in applying this filter specially in choosing the number of eigenimages, and the length scale of operation of the filter.

In the following section, few examples are shown to demonstrate the applicability of FX-Cadzow in achieving noise attenuation at different scheme, either as a single filter or sometimes in combination with other filters for noise suppression and continuity enhancement and signal preservation.

Implementation and Examples

Land seismic records are very noisy; they are contaminated with both coherent and random noises, which is why there is all the more necessity of various passes of noise attenuation at different stages of processing. Adding to the woes the signal strength is also very weak, so the noise attenuation schemes should be such that the signals are retained with proper amplitude fidelity.

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As quite apparent from the theory that this method can be suitably used any form of time series data but it is up to the processors to use them judiciously. Before pre-stack migration it is suitable to apply this filter in shot-receiver domain, while after pre-stack migration it is suitable to apply on the common image pint and offset domain.

The suggested methodology that is adopted is as follows. The shot records prior to migration are chosen as the input. The reflections are flattened with a suitable NMO velocity. Once the gathers are 'dip-restricted' the FX-Cadzow filtering seems to work well. Once the reflectors are flat a 'harsh' filter seems to work. A rough velocity estimate can work the trick in such cases. But a very harsh filter, *i.e.*, choosing very few eigenvalues to retain or a very large filter length can sometimes deteriorate the stacking quality. Therefore, ideally the filter can be applied at a later stage with a good enough velocity estimate available and suitable residual statics already applied on the data. Since the Hankel matrix is computed on individual frequencies therefore the filter can be operated on a suitable bandwidth only. This will control the intensity of the filter. An impact of such filters on the gathers is discussed below.

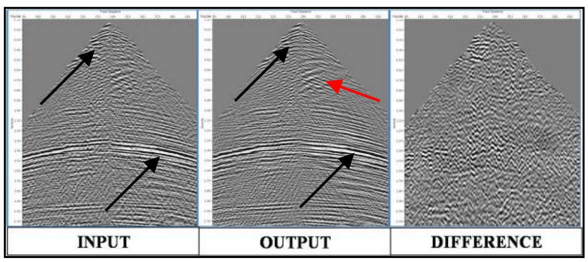

Figure 1: Continuity enhancement of the reflections on application of FX-Cadzow Filtering.

From Fig. 1 it is clear that considerable noise attenuation takes place in the areas marked with black arrows. But it is still felt there are some remnant coherent noises (red arrows) which are not removed by this type of filtering. The reason may be application of mild filter parameters which is preserving more eigenimages. It is also perceived that the noise is coherent over the filter length therefore it is retained. So, it is very important to apply coherent noise removal before applying this filter.

So, a second workflow is further suggested which further increases the efficiency of the filter. A FX-prediction dip filter precedes the FX-Cadzow filter to further restrict remnant coherent noise, marked in red Fig.1. Even in this workflow the filter is applied in a band limited sense to modulate the effect of filter application and to retain amplitude fidelity. The gather flatness is a very important concern one might have while applying this workflow. This workflow is therefore to be applied just before migration.

On datasets with very poor signal to noise ratio, a trim-statics is also applied before application of this workflow.

In the figure aside as mentioned we applied the FX-Cadzow and FX-prediction filtering together in a sequence on the same input gather as in Fig.1. Here as we can see the coherent noise is also attenuated to a great deal (marked with green arrows). The efficiency of the FX-Cadzow filter has enhanced when coupled with prediction dip filtering. However, this filter should be used very cautiously.

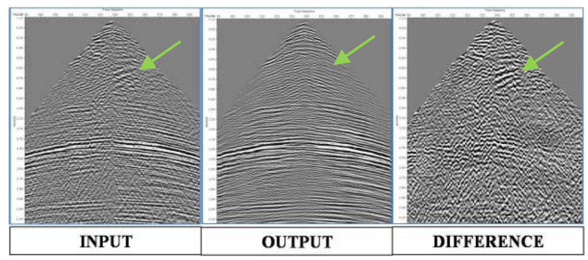

Figure 2: Continuity enhancement of the reflections and removal of coherent noises on application of FX-Cadzow Filtering and FX-prediction Filtering

The figure above demonstrates the efficacy of the workflow. The workflow attenuates the coherent noise and accentuates the signal content. The relative amplitude preservation along the main reflector is also noticed.

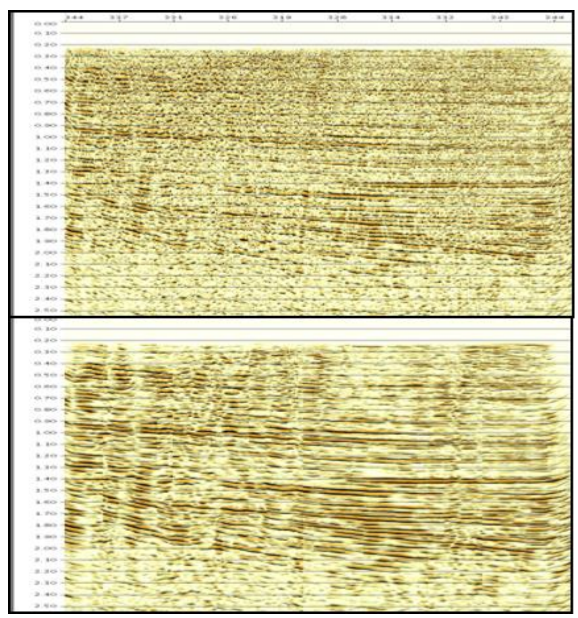

Figure 3: Continuity enhancement and random noise attenuation is perceived on a common offset gather (900 m) after applying FX-Cadzow

The FX-Cadzow filtering can also be implemented on the common offset gathers (Figure 3). The workflow is particularly suitable for gathers post migration. The data is sorted in common offset planes and FX-Cadzow is implemented on them. Since the filter works best in preserving dips only within a particular window and particular band-width, it would be intuitive to choose lesser number of eigenimages (dips) within a limited window (spatial and temporal) to achieve cleaner offset gathers for preserving signal amplitude. The proper modulation of parameters delivers a suitable result as shown in Figure 3.

Finally, for further clarity in the deliverables, it is often recommended to apply the filter on the stacks. Any remnant noise which remained unattenuated may be tackled in the stacks. To avoid smearing of events it may be worthwhile to apply the filter only for the higher frequency band and retain a considerable number of eigenimages. An application of the filter on the stacks is demonstrated in Figure 4.

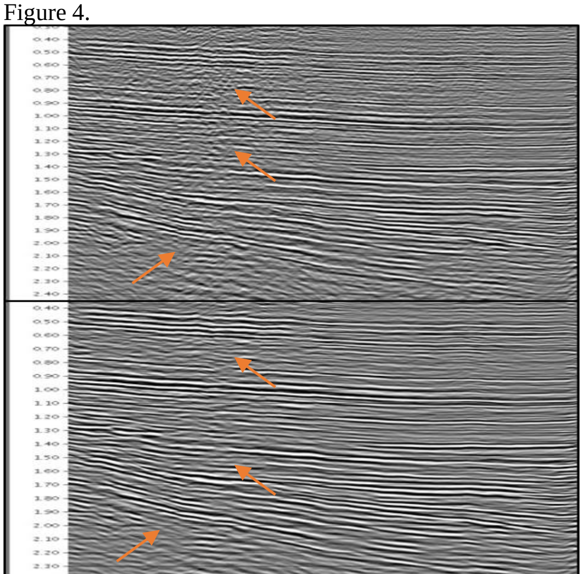

Figure 4: Continuity enhancement of the reflections and removal of noises especially on those areas indicated is seen on application of the filter in post-stack processing sequence

Conclusions

The FX-Cadzow is based on eigenimages decomposition. The construction of the Hankel matrix formulation makes it faster to compute the eigenimages. The restriction of eigenimages controls the amount of dip or coherent energies preserved.

The filter is versatile as it can be used in various instances within the processing sequence. It can be used in different gathers sorted into different schemes in both pre and post stack processing sequences. However, it is often recommended to use it after correcting for residual statics and deriving a time velocity model for flattening the gathers.

It is also demonstrated that since the FX-Cadzow filter mainly targets the incoherent noise, it would be worthwhile to introduce a dip-based filtering preceding the FX-Cadzow filter to restrict some of the coherent dips prior to random noise attenuation.

The filter also provides controls such as spatial and temporal window of operation, number of dips to essentially filter, and band-limit of operation to modulate the strength of the filter. Since the filter operates on the frequency domain it is quite intuitive to target a specific noise band for operation of the filter. This operation would also reduce smearing.

It also clearly observed in the given examples that the relative amplitudes of the events are preserved after application of the filter. This ensures that pre-stack amplitude distribution in the gathers are not perturbed and hence the gathers are compliant for pre-stack inversion studies. Thus, the filter described here is a diverse, effective and is compatible for noisy data preserving fidelity of amplitudes even for low signal energy.

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