Application of Seismic Instantaneous Attributes in Gas Reservoir Prediction

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Abstract: The seismic instantaneous attributes contain a large amount of reservoir information, which can effectively identify oil and gas reservoirs. When extracting the instantaneous attributes of complex seismic signals, the Hilbert-Huang transform has higher time-frequency resolution than the traditional non-stationary signal time-frequency analysis, and the extracted seismic instantaneous attributes can better reflect the signal local features. In this paper, the mode mixing and end effect of the Hilbert-Huang transform are improved, and this new method is used to extract the instantaneous amplitude, instantaneous frequency and instantaneous phase of the seismic signal. The time-frequency analysis of the actual seismic profile is used to verify the effectiveness of the new method, and the relationship among instantaneous attributes, geometric properties and physical properties of reservoir is further studied. This method is effectively applied to reservoir prediction.

1. Introduction
The instantaneous amplitude attributes of seismic signal are often used to determine lateral changes in fluids, lithology, and bottom layers in the reservoir; instantaneous phase attributes can describe the continuity of the formation; low-value anomalies in the instantaneous frequency profile often correspond to gas-bearing sandstones. Oil and gas reservoir characteristics can be more comprehensively described by analyzing instantaneous attributes. Since the seismic signal is a nonlinear and non-stationary complex signal⁹, and the traditional methods used in the processing are mostly based on the processing method of stationary and linear signals. Therefore, there are many problems in the results. In 1998, Professor N.E.Huang proposed a new signal processing technology, namely Hilbert-Huang Transform, HHT⁴. The method first decomposes the signal into the sum of finite Intrinsic Mode Function (IMF) components by Empirical Mode Decomposition (EMD), and then performs the HHT on the IMF components to obtain its instantaneous parameters⁶. The biggest difference between this method and other time-frequency analysis methods is that this method does not depend on the selection of window function or basis function. Its basis is adaptively generated according to the the signal features, and the results can better reflect the signal itself, which makes the time frequency resolution greatly improved.

However, the problems of mode mixing and end effect in Hilbert-Huang transform will all affect the effects of HHT processing⁸. In 2011, Torres proposed the a method of Complete Ensemble Empirical Mode Decomposition, CEEMD⁸, which effectively improved the conventional EMD method. In 2013, Han and Vander Baan used CEEMD to perform time-frequency analysis of seismic signals. The study shows that CEEMD is more sensitive to micro-geological structures; In 2014, Wang
Jiao, etc. proposed a wavelet threshold de-noising method based on CEEMD\cite{12-14}. Based on previous researches, CEEMD method based on AR model prediction is adopted to extract IMF components, and normalized Hilbert transform method is used to obtain seismic instantaneous attributes in this paper. Then the improved method is applied to the seismic data of a certain block to find out the instantaneous attributes and the corresponding relationship between the block oil and gas reservoir features, and predict the oil and gas enrichment region of this block effectively.

2. Improved Instantaneous Attributes Extraction Method

The conventional HHT method obtains the IMF components by using empirical mode decomposition (EMD). This method has the problem of end effect and mode mixing, which directly affects the accuracy of the result.

The end effect occurs in the envelope fitting of the signal. Usually, the upper and lower signal envelopes are obtained by cubic spline interpolation, and the envelope shape is determined by the extreme point. The endpoint of the signal is usually taken as the extreme point when performing EMD, which causes the shape of the envelope to be inconsistent with the actual signal. The end effect does not only affect the vicinity of the signal endpoint. In a continuous screening process, the error is substituted into the next envelope fitting each time. This divergence will gradually spread inside the signal, resulting in serious distortion of the decomposition results.

When there is a signal with intermittent high-frequency oscillation, the traditional EMD will have the problem of mode mixing, that is, there will be a mixture of high-frequency and low-frequency components in the obtained IMF components, and the components will affect each other. However, there are often random noises in seismic signals. When performing EMD on signals containing noise, the low-order IMF that should reflect the high-frequency components of seismic signals are usually mixed with low-frequency components, and the results must have large errors.

To solve the above problems, this paper adopts the CEEMD method based on AR model. The principles of this method are as follows:

1) First, a Gaussian white noise \(n(t)\) with a unit variance of 0.1-0.4 and a mean value of zero is added to the pending signal \(x(t)\), the signal-to-noise ratio of the \(j\) order IMF is defined as \(\varepsilon_j\), which is usually 0.2. The noise is added in a positive and negative pair and repeated \(i\) times to obtain a total of \(2i\) signals, \(x_{1}(t)\) and \(x_{2}(t)\).

2) The AR model prediction is adopted to the acquired signals \(x_{1}(t)\) and \(x_{2}(t)\), and the additional maximum and minimum points that conform to the characteristics of the signal are predicted at both ends of the signal.

If there are a number of \(p\) data \(\{x(np), x(n-p+1), \cdots, x(n-1)\}\) before \(x(n)\) are known, \(\hat{x}(n)\) is the predicted \(x(n)\) value based on these data characteristics, then it can be expressed as

\[
\hat{x}(n) = -\sum_{k=1}^{p} a_k x(n-k)
\]

\(e(n)\) is the error between the predicted value \(\hat{x}(n)\) and the true value \(x(n)\), which has the following relationship:

\[
\rho = E(e^2(n)) = E\{[x(n) + \sum_{k=1}^{p} a_k x(n-k)]^2\}
\]

According to the orthogonal principle, when the sequence \(\{x(n), x(n-p+1), \cdots, x(n-1)\}\) is orthogonal to the prediction error sequence \(\{e(n)\}\), the \(\rho\) value is the smallest. From this, the linearly predicted Wiener-Hopf equation can be derived, where \(r_x(m)\) represents the autocorrelation sequence of the signal \(x(n)\):

\[
\sum_{k=1}^{p} a_k r_x(m-k) = -r_x(m), \quad m = 1, 2, \ldots, p
\]

\[
r_x(0) + \sum_{k=1}^{p} a_k r_x(k) = \rho_{\text{min}}
\]

After the coefficient \(\{a_k\}\) in the equation is obtained by the Levinson-Durbin algorithm, the predicted value \(\hat{x}(n)\) of the true value \(x(n)\) can be obtained. Then, the predicted value \(\hat{x}(n+1)\) of \(x(n+1)\) at \(n+1\) time can be predicted by using the new sequence \(\{x(n-p+1), \cdots, x(n-1), \hat{x}(n)\}\). By analogy, the predicted value of the discrete signal can be obtained at any time.
To extend the two ends of the signals $x_1(t)$ and $x_2(t)$ by AR model, predict the additional extreme points, construct new signals $x'_1(t)$ and $x'_2(t)$, fit the envelope of the new signals, subtract the envelope mean value $m_i(t)$, intercept the extension of the signals and restore the original length, the residual signals $h_1(t)$ and $h_2(t)$ can be obtained as shown below:

$$h_1(t) = x'_1(t) - m_1(t)$$  \hspace{1cm} (5) \\
$$h_2(t) = x'_2(t) - m_2(t)$$  \hspace{1cm} (6)

(3) Verify if the residual signals meet the IMF requirements. If not, then $h_1(t)$ and $h_2(t)$ are considered as the new pending signals. To repeat step (2) and perform k times screening process until the residual signals meet the IMF conditions or end the screening process when the standard deviation of the two consecutive screening results is between 0.2 and 0.3. The result of k times’ screening process can be expressed as:

$$h_{ik}(t) = h_{i(k-1)}(t) - m_{ik}(t)$$  \hspace{1cm} (7) \\
$$h_{ik}(t) = h_{i(k-1)}(t) - m_{ik}(t)$$  \hspace{1cm} (8)

Then obtain population mean of the i-group signals :

$$c_1(t) = \frac{1}{i} \sum_{i=1}^{i} [h_{ik}(t) + h_{ik}(t)]$$  \hspace{1cm} (9)

At this point, $c_1(t)$ is the first order IMF component of the signal $x(t)$.

(4) By subtracting the first order IMF component $c_1(t)$ from the original signal $x(t)$, the first order residual $r_1(t)$ can be obtained. Then define the signal-to-noise ratio $\varepsilon_2$ of the second order IMF component and continue to add the i-group Gaussian white noise $n(t)$. Repeat steps (2) and (3) to find the second order IMF component $c_2(t)$ and the second order residual $r_2(t)$:

(5) Repeated step (4). Stop the decomposition process when the maximum value of the residual is not more than two after j repetitions, and the final residual $r_j(t)$ can be obtained. The original signal $x(t)$ can now be expressed as:

$$x(t) = r_j(t) + \sum_{i=1}^{i} c_i(t)$$  \hspace{1cm} (10)

After the above decomposition process on original signal $x(t)$, the mode mixing and end effect problems existing in IMFs can be well eliminated. By normalizing the IMFs with Hilbert-Huang transform, the instantaneous attributes can be obtained.

3. Profile Analysis of Seismic Instantaneous Attributes

This paper takes the Hangjin Qi Block of Ordos Basin for example, which located on the north edge of the Yishan Slope of Ordos Basin. The upper Paleozoic structure of this target layer is gentle, with only a few nose-like structures and no fractures. Most gas reservoirs are dominated by lithologic control, and a few are dominated by tectonic-lithologic control. The original seismic profile is shown as FIG 1, in the main target layers (1700ms-1900ms) of the Shanxi Group, Taiyuan Group and Shihezi Group, there are mainly four groups of reflection waves: T9b+c, T9d, T9e and T9f, forming a dense reflection section with strong amplitude and good continuity. In the western part of the survey line, the reflection is disordered and discontinuous, and the reflection is merged and bifurcated with the same phase axis. These phenomenon reflect the dramatic changes in the target layer.
In the instantaneous amplitude profile, the amplitude of the reflection section of the reservoir is significantly higher than that of the surrounding area, which can directly reflect the geometry of the reservoir. As shown in the white circle in FIG 2, the fine structure of the reservoir can be clearly identified, revealing that there are more information which is difficult to be directly captured in the original seismic profile.
Figure 3. Seismic Instantaneous Frequency Profile

The normalized instantaneous frequency profile is shown in FIG 3, in which there are several low-frequency areas, and the fine structure of the reservoir in the western part of the survey line is well reflected. Compared with the FIG 2 Seismic Instantaneous Attribute Profile, there is a good correspondence between the low-frequency region and high-value region in the instantaneous amplitude section. The lateral resolution of the instantaneous amplitude attribute is higher, while the vertical resolution of the instantaneous frequency attribute is higher.

Figure 4. Seismic Instantaneous Phase Profile

The seismic instantaneous phase profile is shown in FIG 4, where the continuity of layer can be clearly seen. The bifurcation and dislocation phenomena in the western section of the survey line are more clear and easier to identify, accurately reflecting the spatial overlapping relationship of the reservoir. The bifurcation, merger and interruption phenomenon marked by the white arrow in FIG 4 are more detailed than the original seismic section.

4. Conclusion

In this paper, the conventional HHT method is improved and the improved effect is verified according to the deficiency of HHT method in seismic instantaneous attributes extraction. The relationship between seismic instantaneous attributes and reservoir characteristics is studied for the actual work area data, and the method is effectively applied to the reservoir prediction. The results are shown as follow:

1. The improved HHT method can obviously eliminate the mode mixing and end effect problems that occur in the conventional method and the accuracy of the instantaneous parameters is obviously improved, which prove that this improved method is feasible and effective.
2. The instantaneous attributes of seismic signals can accurately describe the reservoir microscopic characteristics. In the reservoir prediction of this block, the reservoir can be effectively identified by
combining instantaneous amplitude with instantaneous frequency and utilizing the characteristics of strong amplitude of low frequency; The instantaneous phase can reflect the physical change of the formation interface.

There are many solutions to the seismic interpretation, which requires comprehensive interpretation of multiple attributes to accurately describe the reservoir characteristics. It is possible to accurately reflect the specific characteristics of the reservoir and determine the gas-bearing target layer by synthetically analyzing parameters such as instantaneous amplitude, instantaneous frequency, instantaneous phase, etc. as well as the seismic and geological data.

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