Study on the measurement method of oil well’s dynamic liquid level based on air column resonance

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Abstract. A method measuring the depth of liquid surface of oil well based on the resonance principle of air column is proposed in this paper. In the method, air resonance in casing pipe is inspired by sending white noise to oil well continuously, and then dynamic liquid level of oil well can be calculated by analysing frequency spectrum of the experimental resonance signal. Aiming at the problem that the resonance signal contains a lot of white noise, firstly, convolution window function with stronger filtering characteristics is used to improve the signal to noise ratio; then the method of Welch multi segment average power spectrum is used to eliminate noise interference further in frequency domain; finally, the real resonance frequency is measured on the base of the smooth and clear Welch power spectrum, and the depth of the oil well can be estimated effectively. The experimental results show that the above signal processing method can greatly improve the accuracy of measuring the dynamic liquid level depth.

1 Introduction
In the process of oil mining, accurate detection of oil well dynamic fluid level has a very important role in improving oil production efficiency [1,2]. At present, the main method detecting the dynamic liquid level of the oil well is the Echo-method, which obtains the desired infrasound signal through compressing a high intensity shock wave [3,4]. A statistical method based on acoustic signal processing and waveform automatic identification technology to analyse the echo time difference of collar was proposed [5], which had achieved a better measuring result. J.N.MCCOY [6] have studied a double channel echo meter, which can improve the accuracy of the dynamic liquid level depth measurement through analysing both collar waves and liquid level reflected waves. It is found that the nonlinear and non-stationary characteristics of the acoustic signal by filtering are fully preserved through the empirical mode decomposition (EMD) and the solution of instantaneous frequency of the signal, which have a great advantage in acoustic signal filtering [7]. An echo method measuring the propagation velocity of the echo signal based on FFT was proposed to enhance accuracy [8]. However, it is difficult to identify the reflected wave due to the energy’s serious attenuation in the propagation process of acoustic signal of the echo method.

Aiming at the problem of serious energy attenuation in echo method, a method for measuring the depth of oil well based on the acoustic field resonance model is proposed. However, the detection accuracy of the method is significantly affected by inevitable white noise contained in the resonance signal. Therefore, the convolution window function is used to filter noise of the resonance signal on the basis of the window’s strong filtering characteristic, the average value of the resonance frequency about the power spectrum after filtering is estimated. Finally, the accuracy is greatly enhanced through improving the average resonance frequency.
2 Convolution window

For a number of ordinary window \( x_n[n], 1 < n < N \) self-convolution operation, that is \(^{11,12} \):

\[
x_{np}[n] = x_n[n] * x_n[n] * ... * x_n[n]
\]

According to the convolution theorem, the convolution of the function in the time domain is equivalent to the frequency domain multiplication, so the discrete spectrum function of the \( p \)-order convolution window is \(^{13} \):

\[
W_k^p = \frac{\sin^p \left( k\pi \frac{N}{N} \right)}{\sin^p \left( \frac{k\pi}{N} \right)} e^{-\frac{j(\pi - \pi)N}{p}}
\]

\[
= \frac{\sin^p \left( \frac{k\pi}{N} \right)}{\sin^p \left( \frac{k\pi}{N} \right)} e^{-\frac{j(\pi - \pi)N}{p}}
\]

The characteristics of the convolution window’s main and side lobe are increasing significantly with the increase of the convolution’s order. The first-order, sixth-order, twelfth-order and sixteenth-order spectrum of Rectangular convolution window, triangular convolution window, Hanning convolution window and Blackman convolution window which four convolution window’s are compared in Figure 1. The main-lobe of the triangular convoluted window is narrowest and the side lobe attenuation is faster which can be seen from the graph. The main and side lobe's characteristics of the twelfth-order convolution spectrum are not much different from those of the sixteenth-order convolution spectrum, and the de-noising effect of the resonant signal both are good and meet the experimental requirements. But the calculation of the sixteenth-order convolution window is much larger than twelfth-order convolution. Therefore, the twelfth-order convolution window is used to make the experimental analysis.

3 Oil well casing annulus sound field resonance

A method for measuring the depth of oil well based on the acoustic field resonance model is proposed, the pipeline structure is analysed by using the acoustic theory, the mathematical model between the resonance frequency and the length of tube in the air column is established, the length of the air column can be measured by the resonance method. With the change of liquid depth, the length of the air column above the surface of the oil casing pipe is also changing so the dynamic liquid level depth can be estimated indirectly through detecting the air column resonance in the oil ring.
4 Experimental analysis

Based on the method for measuring the depth of oil well in basis of the acoustic field resonance model, in order to detect the resonance signal and analysis its frequency spectrum, a 21-meter-long simulated pipe was constructed. The concrete experimental steps are as follows: (1) Continuous white noise are spread into the oil well, to insure that the sound wave has enough energy to get in touch with the oil surface and reflect back resonances with the incident sound wave; (2) The received signals are adjusted and converted by A/D to convert analog signals into digital signals; (3) Finally, the length of the air column, that is, the depth of the oil well, is calculated according to the resonance frequency.

![Figure 2: The resonance signal acquired in the experiment](image)

![Figure 3: Fourier transform of signal plus twelfth-order convolution window](image)

As shown in Figure 2, we can see that the resonance signal is submerged by a large number of noise signal completely, it is difficult to determine the real resonance frequency by the direct fast Fourier transform (FFT). Because of the excellent side lobe performance of the convolution window, the convolution window is used to reduce the mutual interference between harmonics and improve the accuracy of the harmonic analysis effectively. Twelfth-order rectangular convolution window, twelfth-order triangular convolution window, twelfth-order Hanning convolution window and twelfth-order Blackman convolution window are respectively added to the resonant signal, the obtained spectrums are shown in Figure 3. We can see that there are obvious resonance peaks, and the resonance frequency can be clearly identified, so the accurate air column length can be calculated definitely.
Figure 4: Welch power spectrum of resonance signal with four kinds of convolution windows

Through the research, it is found that the method of Welch multi segment average power spectrum can obtain the clear signal spectrum with a higher resolution and a smaller variance. In order to detect the resonance frequency more accurately, a more accurate spectrum can be obtained after adding the twelfth-order convolution window to the resonance signal and then the Welch power spectrum estimation be made, the result as shown in Figure 4, the experimental data are shown in Table 1. Experimental analysis shows that the spectrum obtained by the welch power spectrum estimation after convolving is very clear to read the resonant frequency accurately, the air column length can be calculated accurately according to the relationship between the resonance frequency and the length of the air column.

Obviously, the resonant frequency obtained by further analysis after filtering is very accurate, the depth of the oil level is very close to the real value, which indicating that the convolution window does have better filtering characteristics can improve the SNR greatly, therefore, the detection accuracy of the depth of oil dynamic liquid level can be improved greatly.

5 Conclusion

The problem that the resonance signal contains a lot of noise interference in the method, can be solved through convolution window's filtering which made a significant increase in SNR and reduced the impact of spectral leakage effectively. The experimental results show that the relative errors of the oil well depth calculated by convolution window's filtering are very low, all relative errors are less than 1%. The obtained resonant frequency filtered by triangular convolution window with wider main-lobe, lower side-lobe and without negative side-lobe is closest to the real value, whose calculated relative error is also the smallest, which is 0.42%.

Table 1: Experimental data

| C.W     | $f_n$     | $\Delta f$ | $l_r$  | $\Delta l$ |
|---------|-----------|------------|--------|------------|
| Ret6    | 283.2     | 8.15       | 21.14  | 0.21       |
| Tri6    | 316       | 8.22       | 21.07  | 0.09       |
| Hann6   | 208.8     | 8.19       | 21.12  | 0.13       |
| Black6  | 250.1     | 8.21       | 21.20  | 0.20       |
Annotation: The units of \( f_n \) and \( \Delta f \) are (Hz); \( l_r \) is the measured value (m); \( \Delta l \) is absolute error (m).

Acknowledgements
This work was supported by National Natural Science Foundation of China (No.51404051), Foundation and frontier research program of Chongqing Science and Technology Commission (No. cstc2015jcyjBX0089) and Research Foundation of Chongqing University of Science & Technology (No.CK2014B15).

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