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Dynamic liquid level detection method based on resonant frequency difference for oil wells

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Abstract: The dynamic liquid level of an oil well can be used to determine the oil production strategies and analyze the reservoir performance. Therefore, it is important to measure the dynamic liquid level in an oil field. This paper proposes a novel dynamic liquid level measurement method for oil wells, where the resonant frequency difference (RFD) of the resonant acoustic signal in annular is used to calculate the dynamic liquid level. To solve the noise interference problem in the resonant acoustic signal, a spectral fast Fourier transform (FFT) method based on Welch power spectrum is proposed to obtain the RFD. First, the Welch power spectrum approach is employed to process the resonant acoustic signal, and a high-pass filter is designed to filter the inherent envelope of low frequency in the power spectrum. In particular, a clear and smooth power spectrum can be obtained by choosing a suitable window and a sectional length. Furthermore, the short-time Fourier transform method is used to extract the strongest energy spectrum of the power spectrum. Finally, the RFD of two adjacent resonant harmonics can be accurately obtained by using FFT for the strongest energy spectrum. Experimental results show the effectiveness of the proposed approach.

Key words: Dynamic liquid level, resonant frequency difference, Welch power spectrum, fast Fourier transform, filter

1. Introduction

Dynamic liquid level, defined as the distance from the wellhead to the oil liquid level, is a key parameter for oil production. Dynamic liquid level can be used to analyze the oil supply capacity and determine the submerged depth of the pump. Meanwhile, downhole pumping status such as oil pressure, oil production index, and effective permeability can be calculated by using the dynamic liquid level. The dynamic liquid level can be used to analyze the reservoir performance and determine the production strategies. Hence, accurate dynamic liquid level is very important for oil production.

The traditional measurement methods of dynamic liquid level include the pressure gauge detection method [1], float method [2], dynamometry card method [3], optical fiber method [4], and echo method [5, 6]. The echo method is the most widely used for measurement of dynamic liquid level due to simple operation and high efficiency. However, as the acoustic wave propagates into the oil well, the energy attenuation is serious due to the dead oil ring and the foam layer in the oil well. It is difficult to recognize the coupling waves (reflected by oil couplings) and the liquid waves (reflected by dynamic liquid level), because of the interferences of the various mechanical noises and the acoustic noise. Therefore, low accuracy limits the application of the echo method.

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Inspired by the air resonance theory, a novel dynamic liquid level measurement method based on an air column resonant model was proposed in our previous work [7, 8]. Different from the traditional echo method, in the novel method the dynamic liquid level can be estimated by measuring the resonant frequency of the air of the annular. In order to make the air resonance, a continuous white noise wave is generated at the wellhead. Although the novel method can avoid recognition of the coupling wave and the liquid wave from the strong noise, it is difficult to accurately detect the resonant frequency from the weak resonant harmonic signals with strong noise background.

In the past decades, researchers proposed many methods to extract frequency from strong noise signals. In [9, 10], multiresolution characteristics of the wavelet transform method were presented to extract the frequency characteristics of a high frequency resonant pulse signal with strong noise interference. However, it is difficult to choose a suitable wavelet base and decomposition layer, which leads to instability of wavelet analysis, especially under strong noise interference. Meanwhile, the useful signal was filtered due to the inappropriate wavelet threshold. In [11, 12], a time domain autocorrelation method was proposed to reduce the noise interference, and then auxiliary methods were used to extract the ideal frequency feature. In [13, 14], a frequency domain autocorrelation approach was adopted to filter out the noise interference in the frequency domain, which makes frequency characteristics of the useful signal more evident. If the signal-to-noise ratio is too low, the denoising effects can only be achieved after multiple autocorrelations. However, with the increase of the number of autocorrelations, the calculations will greatly increase. The Welch power spectrum method can eliminate noise interference in the frequency domain by using the multisegment average of the spectrum. Meanwhile, the Welch power spectrum can reduce the spectrum leakage by adding different window functions. The advantages of Welch power spectrum estimation are very suitable for harmonic frequency detection under noise interference [15–18]. At the same time, Welch power spectrum estimation has the characteristics of high computational efficiency and fast data processing speed. For the resonant signal, the frequency difference of the adjacent resonant harmonic is getting smaller and smaller as the depth of the well increases. Moreover, the noise interference in the frequency domain relatively increases as the energy of the resonant signal decreases. Due to the above factors, it is difficult to accurately extract the frequency characteristics of the resonant signal.

To address these concerns, a spectral FFT method based on the Welch power spectrum is proposed to extract the RFD from resonant harmonic signals with strong noise background. First, the power spectrum of the resonant signal in annular is obtained by using the Welch power spectrum estimation method. Then a new period spectrum is achieved by filtering the low frequency envelope interference in the power spectrum. Furthermore, the short-time Fourier transform is used to select the region of the spectrum with strong energy. Finally, a characteristic spectrum of the resonant signal is obtained using FFT for the selected region.

The rest of this paper is organized as follows: Section 2 briefly reviews the measurement method of the dynamic liquid level. Section 3 presents the detailed RFD extraction method based on the proposed filter approaches. In Section 4, the proposed algorithm is applied to the simulated oil tubing, and the experiments and results are discussed in detail. Finally, the conclusion is provided in Section 5.

2. Measure principle

Based on the resonance principle of air columns, the mathematical model of the length of an air column and its resonant frequency is established as follows [7, 8]:

$$f_n = \frac{(2n-1)v_c}{4l}, n = 1, 2, 3, \dots, \quad (1)$$

where n is the harmonic order number, f_n is the corresponding harmonic frequency, and l is the length of the air column. The resonant frequency of the adjacent wave can be expressed as:

$$f_{n+1} = \frac{(2n + 1) v_c}{4l}, n = 1, 2, 3, \dots . \tag{2}$$

Combining Eqs. (1) and (2), we have

$$l = \frac{v_c}{2\Delta f}, \tag{3}$$

where Δf is the RFD of two adjacent resonant harmonics and v_c is the speed.

In real applications, the oil well nozzle should be considered. Hence, (3) can be rewritten as:

$$l = \frac{v_c}{2\Delta f} - 0.3d, \tag{4}$$

where d is the casing diameter of the well. Therefore, the length of the air column, namely the depth of the oil turbine surface, can be calculated by measuring the resonant frequency. In the following, we introduce the proposed method to calculate the RFD.

3. RFD extraction

The ideal resonant acoustic waves can be engendered by transmitting continuous white noise waves into annular space of the oil well. However, the resonant acoustic waves are inevitably mixed with a variety of noises, where the interference of white noise is largest. Meanwhile, the resonant acoustic wave is also very weak due to the great depth and complex environment of the real oil. Figure 1 shows a resonant acoustic signal collected from the oil casing. It is obvious that the resonant signal is completely submerged by the white noise. In this paper, first we use the Welch power spectrum to process the resonant signal. Then a high-pass filter is designed to filter the low-frequency envelope of the Welch power spectrum. Furthermore, a short-time Fourier transform is employed to select the largest amplitude region of the Welch power spectrum. Finally, the FFT method is used to obtain the RFD. In the following, we introduce the proposed method in detail.

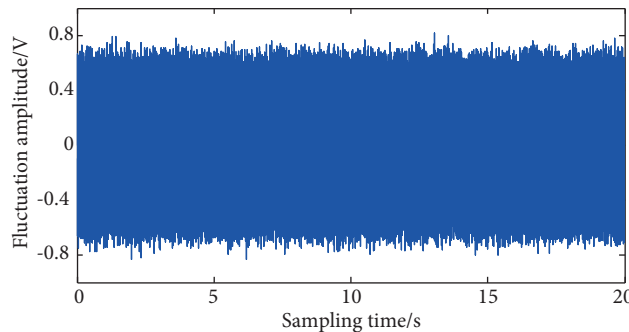


Figure 1. Time domain of a resonant signal collected from the oil casing.

3.1. Welch power spectrum

The Welch power spectrum is a widely used method in spectrum estimation [19, 20]. The data are divided into several segments with equal intervals, and then we can obtain the power spectrum of each segment. Assume the

sampled data are divided into L segments with each length M , that is, $N = L * M$. After adding the window, the data of the i th segment become

$$x'_N(n) = x_N[n + (i - 1)M]d_1[n + (i - 1)M], \tag{5}$$

where $0 \leq n \leq M - 1, 1 \leq i \leq L$. $d_1(n)$ is the window with length of M . Calculating the power spectrum of each segment separately, $\hat{P}_{per}(w)$,

$$\hat{P}_{per}(w) = \frac{1}{M} \left| \sum_{n=0}^{M-1} x'_N(n)e^{-jwn} \right|^2, 1 \leq i \leq L. \tag{6}$$

The average of each $\hat{P}_{per}(w)$ can be expressed as

$$\bar{P}_{per}(w) = \frac{1}{L} \sum_{i=1}^L \hat{P}_{per}(w) = \frac{1}{ML} \left| \sum_{n=0}^{M-1} x'_N(n)e^{-jwn} \right|^2. \tag{7}$$

When the frequency resolution is met, the Welch power spectrum estimation can reduce the noise interference by using the multisegment average in the frequency domain and reduce the influence between the harmonics by adding the suitable window function. Therefore, the Welch power spectrum is more clear and smooth under the noise background. The overlap of the data has no obvious change for the variance of the power spectrum [21]. In this paper, FFT points are set to 4 times the segment data, and the window function is a Hanning window. Figure 2 shows the Welch power spectrum of the resonant signals of Figure 1. It can be seen that the energy of the low frequency DC is too high, resulting in the periodicity of the power spectrum not being obvious. The harmonic frequency cannot be shown clearly through the simple Welch power spectrum. Therefore, the direct Welch power spectrum cannot be used to accurately calculate the RFD (Δf).

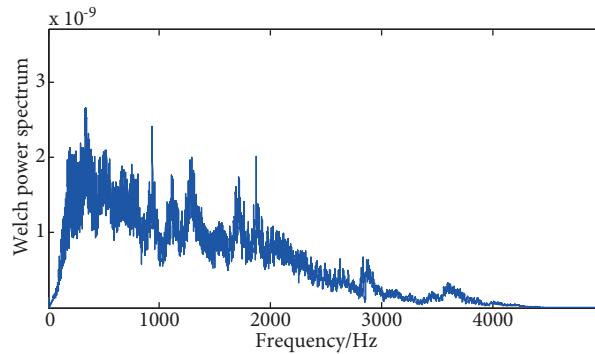


Figure 2. Welch power spectrum of Figure 1.

3.2. Filtering process

In theory, the spectrum of resonant harmonics consists of approximate pulse signals, which are the integral multiples of the harmonic fundamental frequency; namely, the spectrum is periodic. However, the interval of adjacent wave crests is not strictly equal in the Welch power spectrum due to the noise interference. As the spectrum of periodic pulse signals is also periodic, the interval (Δf) between two adjacent resonant harmonics

can be extracted from the frequency domain by using FFT. Therefore, in order to obtain a periodic power spectrum, we design a high-pass filter to filter out the low frequency component of the Welch power spectrum. For Figure 2, the result of high-pass filtering is shown in Figure 3. From Figure 3, it can be seen that the low-frequency envelope of the Welch power spectrum is filtered out. However, the amplitude of the power spectrum decreases gradually with the increasing of the frequency, which leads to lower accuracy of the useful signal frequency of the FFT spectrum. In order to obtain a more precise Δf , we select a region from the Welch power spectrum that has larger amplitude for further analysis.

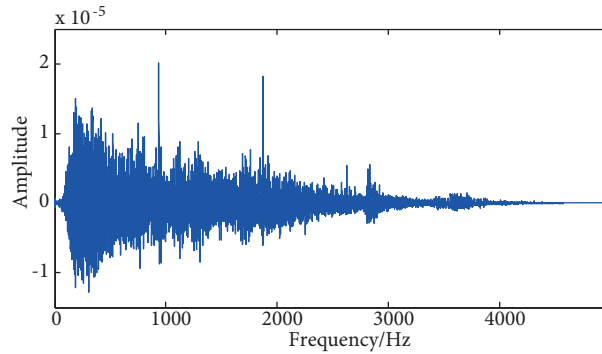


Figure 3. High-pass filtering for the Welch power spectrum.

3.3. Short-time Fourier transform

For a stationary signal whose frequency domain information does not change with time, the traditional Fourier transform can obtain the ideal spectrum of the signal. However, for a nonstationary signal with variation of the spectrum component (frequency size or amplitude size) over time, the spectrum obtained by traditional Fourier transform does not fully reflect the true nature of the signal. However, short-time Fourier transform can obtain the spectrum information of any time period signal by combining time domain analysis and frequency domain analysis. In Figure 3, it is obvious that the harmonic peaks show a certain periodicity; however, there is a large variation in the amplitude. If the amplitude is too small, it will certainly be influenced by the strong noise. Hence, the spectrum after FFT will be completely submerged. To improve the signal-to-noise ratio, short-term transformation is used to select the spectrum with higher energy. The short Fourier transform spectrum of Figure 3 is shown in Figure 4a, where the window length is 400 points and the window center moves 100 points each time. Figure 4b shows that normalized frequency 24 represents the resonant harmonic; the resonant signal from 6 to 43 in the y-axis direction is the strongest.

3.4. Fast Fourier transform

The FFT of the power spectrum selected by short-time Fourier transformation is shown in Figure 5. The interference of the noise in Figure 5 is relatively reduced and the accuracy of the target frequency is increased. Finally, the spectrum line with maximum amplitude was converted to the frequency difference of the adjacent resonant harmonic. The points of the power spectrum selected by short-term Fourier transform are set as N , f_s is the sampling frequency, and N_1 is the number of points of each segment in the Welch power spectrum. n represents the normalized frequency of the peaks in the final FFT spectrum, and the normalized frequency of the FFT based on MATLAB is one more than the actual value. Therefore, the normalized frequency of the periodic peak is $n_1 = n - 1$. After using FFT, n_1 is the number of the periodic signal in the power spectrum

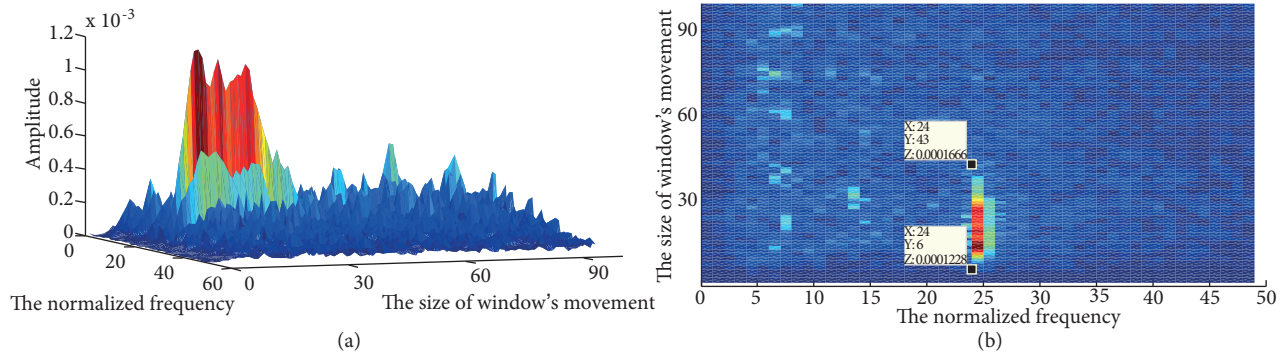


Figure 4. The short-time Fourier transforms results: (a) time-frequency diagram; (b) two-dimensional projection.

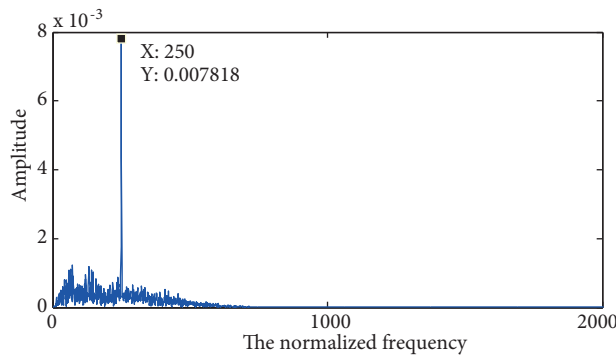


Figure 5. FFT spectrum of regional power spectrum.

region (length is N), and then the number of points in the periodic signal is N/n_1 . The interval between the adjacent wave crests in the power spectrum is f_s/N_1 , namely the resolution. Therefore, the formula for the RFD of the adjacent resonant harmonic can be expressed as

$$\Delta f = \frac{N}{n_1} \frac{f_s}{N_1} = \frac{N}{n-1} \frac{f_s}{N_1}. \tag{8}$$

4. Experiments and discussion

Experiments are carried out on a simulated oil tubing. The resonant signal can be obtained by transmitting a continuous white noise signal into the oil tubing. The corresponding devices are used to detect and process the obtained resonant signal. After obtaining the resonant signal, the proposed method is used to obtain the RFD and calculate the dynamic liquid level. The experimental procedures are as follows:

Step 1: A white noise signal is generated by the sound software, and the signal is set out through the external power amplifier and speaker.

Step 2: The white noise is transmitted into the oil casing to make the air column of the annular resonance.

Step 3: The sound pickup is placed at the rim of the oil casing and collects the air column resonant signal in the oil casing.

Step 4: Gain adjustment for the collected signal is used to adjust its energy to an appropriate range.

Step 5: The signal is passed through the low-pass filter for anti-aliasing filtering, and then performs A/D conversion, and finally inputs the digital signals into the computer.

Step6: The signal processing method proposed in this paper is used to analyze the resonant signal in order to obtain the RFD.

The length of the simulated oil tubing is 61.42 m and 123.8 m. The corresponding parameters are set as follows: sampling frequency is 10,000 Hz, sampling time is 3 min, cut-off frequency of the anti-aliasing filter is 4000 Hz. For 61.42 m of oil tubing, the window length of measurement data is 20,000 points and the resolution ratio is about 1 Hz. For 123.8 m, the window length of measurement data is 100,000 points, and the resolution ratio is about 0.2 Hz. The speed of sound can be calculated by $v_c \cong 331.45 + 0.61t(m/s)$ at normal atmospheric pressure, t is temperature. The temperature of the experimental environment is 13 degrees centigrade and the inner diameter of the pipe is 0.075 m. The relationship between the length of the experimental air column and the resonant frequency is:

$$l = \frac{169.69}{\Delta f} - 0.0225(m). \tag{9}$$

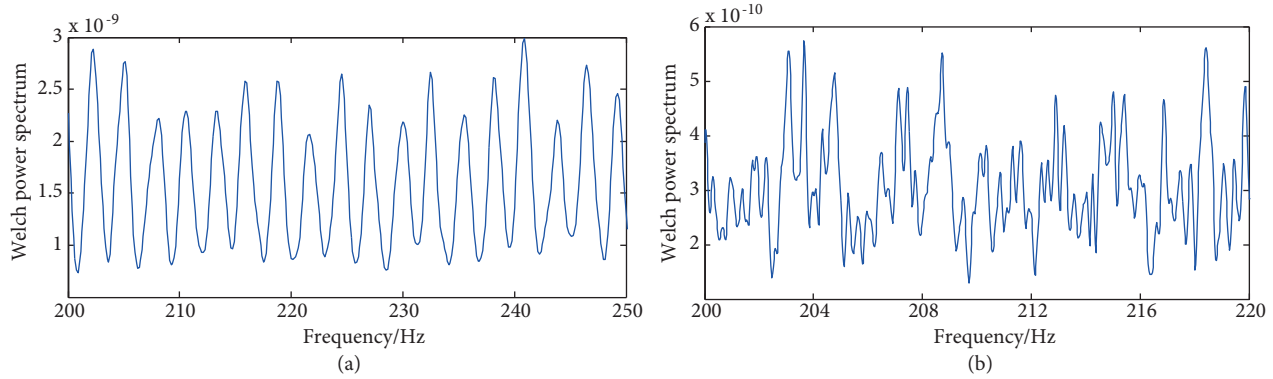


Figure 6. Welch power spectrum estimation of resonant signal: (a) 61.42 m oil well pipe; (b) 123.80 m oil well pipe.

The Welch power spectra of the experimental oil tubing are shown in Figure 6. Resonant harmonics are generated in the simulated oil tubing. The frequency difference of the adjacent resonant harmonic becomes smaller as the length of oil well pipe increases, and it is difficult to obtain the Δf from the Welch power spectrum directly. Moreover, the interference of noise becomes more and more strong.

Using high-pass filtering, short-time Fourier transform, and FFT to analyze the Welch power spectra of Figure 6, it can be seen that the spectrum lines (Δf) are very obvious, as shown in Figure 7. Noise interference still exists; however, the faint noise has no effect on Δf . The experimental results for different lengths of the oil tubing are summarized in the Table, where l_m and l_a are the measured length and the actual length of the simulated tubing, respectively. Δl and E represent the absolute error and relative error, respectively. It is obvious that the measurement accuracy of the length of oil well pipe is high, and the relative error does not increase significantly as the length of pipe increases.

In addition, the energy and the propagation distance of acoustic waves will decrease if the propagation direction of the acoustic waves is changed. The measurement results in our experiment are still accurate, although the pipe has bent 90 degrees. The measurement results indicate that continuously transmitting white noise into the oil tubing is necessary. The continuous white noise will provide continuous energy to guarantee the resonance of the air in the actual oil well.

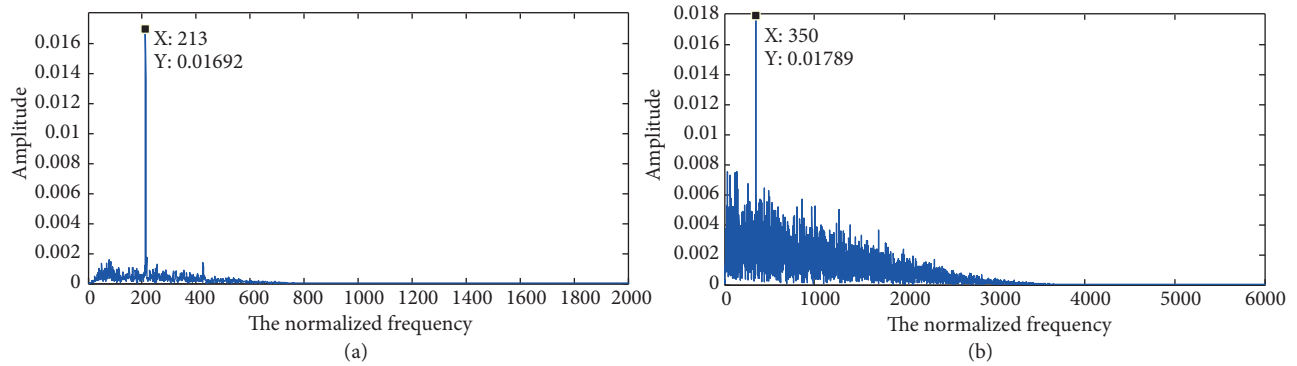


Figure 7. FFT spectrum of power spectrum: (a) 61.42 m oil well pipe; (b) 123.80 m oil well pipe.

Table. Experimental results for different lengths of the oil tubing.

f_s (Hz)	N	n	N_1	Δf (Hz)	l_m (m)	l_a (m)	Δl (m)	E (%)
10000	5800	96	80000	7.632	22.213	22.27	0.057	0.26
10000	4700	213	80000	2.771	61.21	61.42	0.210	0.34
10000	4100	250	80000	2.058	82.42	82.73	0.308	0.37
10000	19200	350	400000	1.375	123.35	123.8	0.444	0.36

5. Conclusions

In this paper, we propose a novel dynamic liquid level detection method based on air column resonance for oil wells. To obtain the dynamic liquid level, a spectral FFT method based on the Welch power spectrum is proposed to calculate the RFD of the resonant acoustic signal. First, a suitable window function is chosen to reduce the interference of the harmonic leakage, and a high-pass filter is designed to filter the inherent envelope at low frequency of the power spectrum. Then, in order to improve the signal-to-noise ratio, short-time Fourier transform is employed to process the power spectrum of the resonant acoustic signal. Using the proposed method, we can obtain the frequency difference of the adjacent resonant harmonic and it can calculate the dynamic liquid level of the oil well conveniently. The proposed method can be applied to measure the dynamic liquid level of the oil well and can provide a new inspiration for measuring dynamic liquid levels for complicated oil wells.

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