Echo recognition and correction for guided wave radar level based on adaptive LMS

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Abstract: The radar echo signal of non-stationary and singular points usually contains false echoes, which affects the recognition and measurement of liquid level echo signal. In order to eliminate false echo interference and improve the recognition and measurement accuracy of the liquid level gauge, a method of echo recognition and correction based on adaptive least mean square (LMS) is proposed. The short-time amplitude function and short-time zero crossing rate function are combined to recognize the echo signal. The weight vector iteration and updating weight coefficients are obtained by LMS method. The echo signal is recognized and the false echo interference is suppressed. The experimental results show that the level echo signal can be accurately recognized by this method, and level measurement accuracy can reach 0.47% F.S. Compared with other denoising methods, adaptive LMS can keep the signal singularity characteristics while suppressing the noise. Moreover, it has better robustness.

Key words: guided wave radar; liquid level gauge; least mean square (LMS); echo correction

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0 Introduction

Guided wave radar level gauge is a new type of liquid level measuring instrument. Level is measured by time-domain reflection principle[1]. The method has some advantages: measurement stability, high accuracy, corrosion resistance, strong adaptability, high performance, better implementation of the inflammable and explosive. This measurement method is widely used in industrial areas. The high temperature and high pressure liquid level can be achieved by this method. The liquid level measurement system of guided wave radar contains many kinds of reflected echo beams including the guided wave probe that connects to the top echo and the liquid level surface echo[2-4]. Therefore, there are two difficulties in measuring the height of the liquid: the correct recognition of the liquid level echo and the accuracy of measurement. The former is the basis of the latter. Traditionally, the echo wave crest is determined by the maximum value method[5-8]. There are disadvantages that the liquid level echo condition is single, meanwhile, the normalized variance of the parameter is large. These two shortcomings are prone to misjudgment when the liquid level is close to the long distance measurement level. Therefore, the anti-jamming is poor, the blind area is large and the liquid level measurement accuracy is not high.

In order to eliminate false echo interference and improve the measurement accuracy of the liquid level meter, a method with the pseudo-level echo interference by short-time amplitude function and short-time zero crossing rate function[9-12] to accurately recognize the real level echo is proposed in this paper. Adaptive least mean square (LMS) filter is used to update the weight coefficient and obtain the optimal estimation, effectively eliminating the irrelevant echo beam interference and improving the reliability of echo recognition and level measurement accuracy.

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1 Liquid level echo recognition

The liquid level echo signal will form a reflection echo when the level gauge casing is bent. This reflection wave can be severed as the liquid level echo due to the level gauge installation problem, which is called as pseudo level echo. Therefore, recognition of liquid level echo is a key factor to improve the accuracy of liquid level measurement. In order to solve this problem, this paper analyzes the echo characteristics of true liquid level. The liquid level echo shows up the characteristics of low frequency and short time energies by a large number of experimental data. The short-time zero crossing function and the short-time amplitude function are used to process the echo signal frame to recognize the liquid level echo. Figs. 1 and 2 are the signal distributions of the noise applied to the liquid level echo.

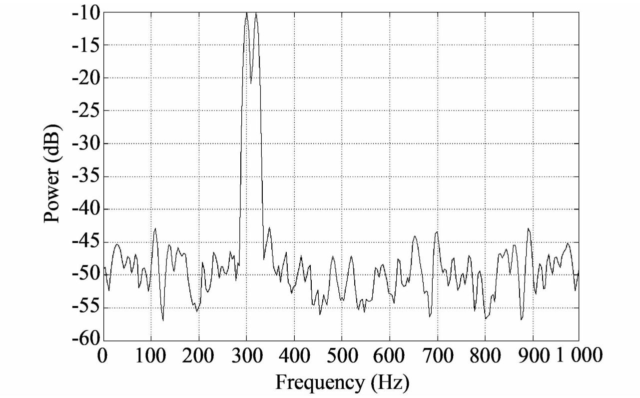


Fig. 1 Noise level of smaller level echo signal

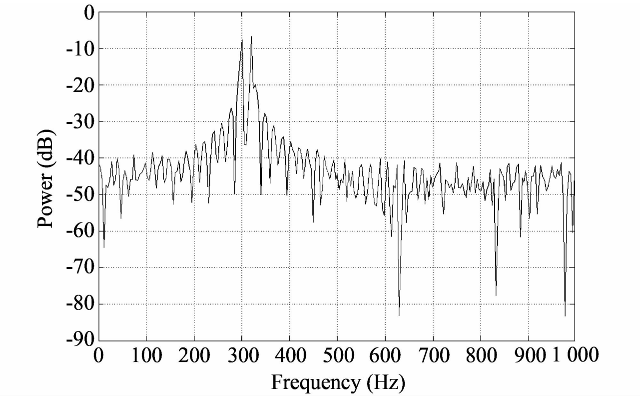


Fig. 2 Noise level of larger level echo signal

The time domain sampling value of echo signal is $x(n)$. The frame shift is L, the frame length is K. The window function is $m(n)$, and the signal $x_n(n)$ is processed by the window frame n.

$$x_n(n) = m(n)x(nL - L + n), \tag{1}$$

where $m=1,2,3,\cdots$, $0 \leqslant m \leqslant K-1$; $m(n)$ is square window, its general form can be expressed as

$$m(n) = \begin{cases} 1, & 0 \leqslant n \leqslant K-1, \\ 0, & \text{others}. \end{cases} \tag{2}$$

In order to represent the amplitude of each frame, a short time amplitude function is defined. If the n frame signal short-time amplitude function is expressed by $x(n)$, its expression is

$$T_n = \sum_{n=0}^{N-1} | x_n(n) |^{\gamma}, \tag{3}$$

where γ is the amplitude sensitivity factor, $\gamma > 0$, indicating the sensitivity degree of the short amplitude function T_n to the high amplitude of a frame signal. The short-time zero crossing rate Y_n of the n frame signal $x(n)$ indicates that the frame signal waveform passes through the zero-level number, which can be calculated by the number of sampling symbol changes. The function can be written as

$$Y_n = \frac{1}{2}\sum_{n=0}^{N-1} | \operatorname{sgn}[x_n(n)] - \operatorname{sgn}[x_n(n-1)] |, \tag{4}$$

where sgn[] is a symbolic function. High frequency signal can not return from the liquid level because of the attenuation. The liquid level echo is mainly concentrated in the low frequency, which has a low short-time zero crossing rate. Meanwhile, the function has a high frequency noise in the liquid level echo, making the liquid level echo form a "burr". Therefore, the function will not increase the zero crossing rate. According to the calculation of short-term amplitude T_n and short-term zero-crossing rate Y_n, the function can be defined as

$$B_n = \frac{E_n^a}{Y_n^b + \beta}, \tag{5}$$

where $a, b \geqslant 1$, $a < b$, $0 < \beta < 1$. The degree of influence on the function value B_n is set by selecting the parameter a in the short-time amplitude function of the numerator and the parameter b. The zero-crossing parameters and the signal spectrum of the radar echo signal are analyzed to recognize the level echo in the echo signal.

2 Processing pseudo level echo based on LMS

Set the initial iteration weight vector and adjust the weight vector. As the number of iterations increases, the filter converges to Wiener solution by the gradient descent method. LMS algorithm is not used to calculate the input signal autocorrelation matrix and the cross correlation matrix. The steepest descent gradient estimation is expressed as

$$\overset{\wedge}{\nabla}(k)=\frac{\partial e^2(k)}{\partial w(k)}. \tag{6}$$

The LMS adaptive filtering adopts the transverse filter. The coefficient updating process is as follows: set the initial iteration vector and adjust the weight vector by the gradient descent algorithm. The system includes two input channels. First channel includes the echo signal $S(k)$ and the pseudo echo signal $X(k)$, which is called as the original input channel. Input signal is $S(k)+X(k)$. The other channel $S(k)$ that is not correlated with the pseudo echo signal refers to the reference input channel. According to the adaptive filtering characteristic, the noise $Y(k)$ is automatically adjusted by LMS adaptive filtering to obtain the $Y(k)$ estimation signal. Its general form can be expressed as

$$B(k)=\hat{Y}(k). \tag{7}$$

The system output error signal $E(k)$ is the difference between the original input signal and the reference input signal. Its function can be written as

$$E(k)=S(k)+X(k)-\hat{Y}(k). \tag{8}$$

If the signal $S(k)$, $X(k)$ and $Y(k)$ are statistically stable, the mean square error can be obtained by

$$E[E^2(k)]=E[S^2(k)]+E[X(k)-\hat{Y}(k))^2]+ \\ 2E[S(k)(X(k)-\hat{Y}(k))]. \tag{9}$$

The adaptive filtering processing allows $E[E^2(k)]$ to be minimized. $E[S^2(k)]$ is the signal power. The third term has no correlation with the noise source, and the result is zero. Therefore, the mean square error $E[E^2(k)]$ is the smallest. The second value in the equation is the smallest.

$$E[E^2(k)]_{\min}\Leftrightarrow E[(X(k)-\hat{Y}(k))^2]_{\min}. \tag{10}$$

According to Eq. (9),

$$E(k)-S(k)=X(k)-\hat{Y}(k). \tag{11}$$

In the adaptive LMS criterion, $E[(X(k)-\hat{Y}(k))^2]$ is minimum. Meanwhile, $E[X(k)-S(k))^2]$ is minimized. The LMS adaptive filter output $E(k)$ approaches to $S(k)$. The system output signal $S(k)$ is the best estimation in the adaptive LMS criterion. The system can adaptively select the iterative vector and eliminate false echo interference in radar level gauge through the above analysis processing.

3 Experimental results

3.1 Radar echo recognition analysis

The electromagnetic wave that emitted by the wave simulation radar is severed as the excitation source. The liquid level fluctuations are regarded as the low speed moving target signal. Radar echo generated by radar level meter is shown in Fig. 3.

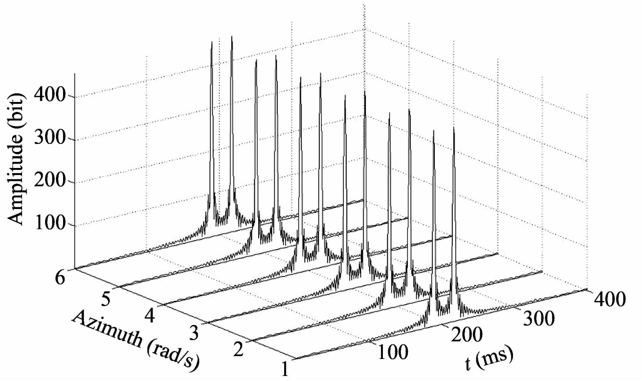


Fig. 3 Radar echo

Meanwhile, carrier frequency is set to 20 GHz. The incident azimuth pitch angle is 90° and the azimuth angle is 0°. Radial echoes of the full-angle angular electromagnetic scattering characteristics can be obtained by interpolation. The liquid level echo signal can be accurately recognized as shown in Fig. 4.

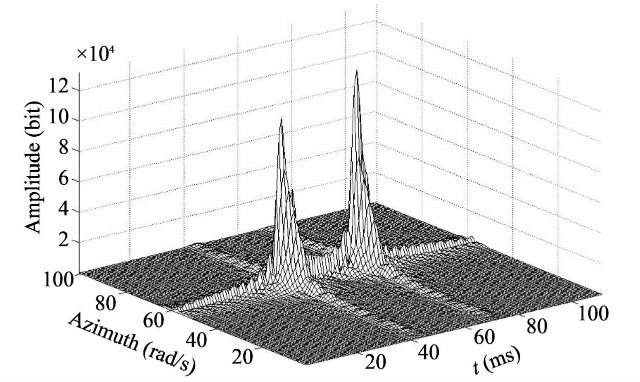


Fig. 4 Liquid level echo recognition

3.2 Liquid level data analysis

The highway addressable remote transducer (HART) communication and central processing unit (CPU) module are used to design the level measurement system as shown in Fig. 5. The system shows the standard and the measured value of the liquid level. The medium is water and maximum range is 850 mm.

The radar level gauge measures 10 sets of data continuously.

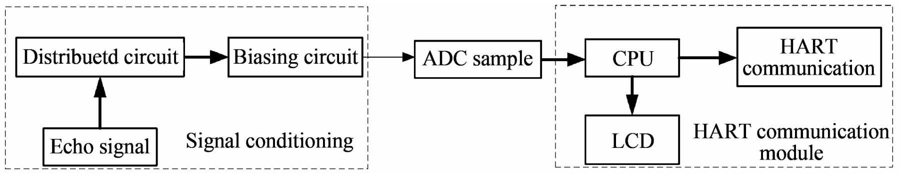


Fig. 5 Level measurement system

The liquid level data in Table 1 is not measured by any filtering method, and liquid level relative error can reach 4.81%. There are echo errors in the inherent defects of the wave radar level gauge.

The liquid level data in Table 2 is measured by the proposed adaptive LMS filter algorithm. The liquid level relative error is significantly reduced and the maximum liquid level error is 3.10 mm. Maximum relative error is no more than 0.47% and accuracy can achieve 0.47% F. S. This paper uses adaptive LMS filtering method to eliminate its false echo interference. Level measurement accuracy is improved.

Table 1 Separate measurement of liquid level data

Standard value (mm)	Measured value (mm)	Error (mm)	Linear error (%)	Direction
240.0	251.6	11.60	4.81	Positive
330.0	341.0	11.00	3.33	Positive
440.0	459.2	19.20	4.40	Positive
690.0	682.4	7.60	1.10	Negative
740.0	726.5	13.50	1.82	Positive
820.0	833.8	13.80	1.69	Positive
520.0	527.7	7.70	1.50	Positive
670.0	658.9	11.10	1.66	Negative
680.0	670.4	9.60	1.41	Negative
565.0	556.0	9.00	1.59	Negative

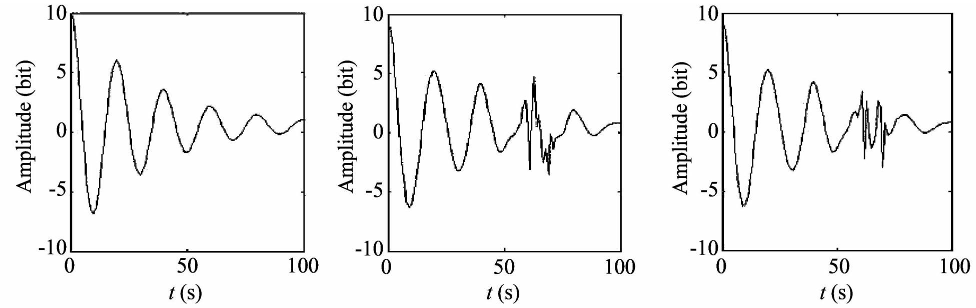
Table 2 Adaptive LMS filtering liquid level measurement data

Standard value (mm)	Measured value (mm)	Error (mm)	Linear error (%)	Direction
240.0	240.6	0.60	0.25	Positive
330.0	331.0	1.00	0.31	Positive
440.0	439.2	−0.80	0.18	Negative
690.0	692.4	2.40	0.34	Positive
740.0	736.5	3.50	0.47	Negative
820.0	823.8	3.80	0.46	Positive
520.0	517.7	1.30	0.44	Negative
670.0	668.9	1.10	0.16	Negative
680.0	680.4	0.40	0.06	Positive
565.0	566.0	1.00	0.18	Positive

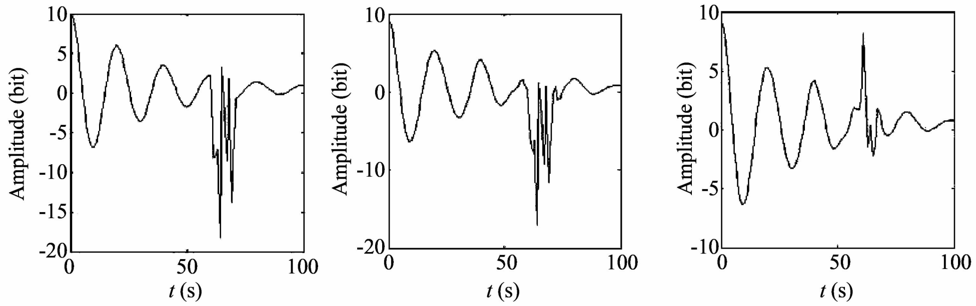
3.3 De-noising analysis

The liquid level echo signal is denoised by using the mean filtering, the least squares method, Ref. [3] method and the proposed method, the comparison results are shown in Fig. 6. The simulation results show that the denoising effect of the adaptive LMS method is better than the other methods. The noise amplitude can be suppressed. Some subtle signals in the noisy signal can enhance the recognition by the proposed method. Moreover, this method possesses good robustness.

The non-linear relative error (NLRE) and the root-mean-square error (RMSE) of the two indicators are shown in Fig. 7. The latter two methods results are better than the traditional method. According to the comparison results of the local peak relative error, the proposed method can preserve the local peak of the signal better than the Ref. [3] method, which is better to keep the local singularity of the signal.



(a) Liquid level echo signal (b) Mean filtering method (c) Adaptive LMS method



(d) Noise liquid level echo signal (e) Least squares method (f) Ref.[13] method

Fig. 6 Comparison of denoising methods

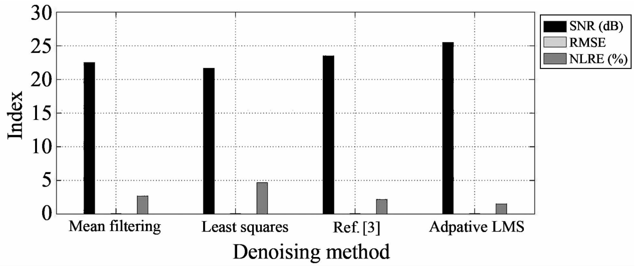


Fig. 7 Comparison of denoising indicator

4 Conclusion

It is proposed to combine the short-time amplitude function with the short-time zero crossing rate function to recognize the true liquid level echo. The LMS filter algorithm is used to adapt the level process of the guided wave radar level gauge. The system weight vector iteration is carried out, and the weight coefficient is updated to avoid the false echo disturbance in the radar echo. The radar level gauge output results are more stable. The liquid level can be converged to the true speed value by this method. The results show that the proposed method can accurately recognize the liquid level echo and reduce the noise amplitude in the liquid level echo. Meanwhile, the adaptive LMS makes the liquid level accuracy conform to the modern industrialization requirements.

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基于自适应LMS的导波雷达液位计回波识别与校正

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摘　要： 非平稳及多奇异点的雷达回波信号包含虚假回波，影响液位回波信号的识别与液位测量。为解决雷达液位计的虚假回波干扰问题，提高液位识别与测量精度，提出一种回波识别与校正方法。将短时幅度函数与短时过零率函数结合，利用函数逐帧地对回波信号计算，识别液位回波信号；通过自适应最小均方误差进行系统的权矢量迭代，更新权系数，对回波信号进行处理，进行抑制虚假回波干扰。实验结果表明：该方法能够准确识别液位回波信号；液位测量精度可达到0.42%F.S，相比于其他去噪方法，该方法在抑制噪声的同时能较好地保留信号奇异性特征，有较好的鲁棒性。

关键词： 导波雷达；液位计；LMS；回波校正

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