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An Improved Positioning Algorithm in Long Range Asymmetric Perimeter Security System

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Abstract—**In this paper, an improved positioning algorithm is proposed for the long range asymmetric perimeter security system. This algorithm employs zero-crossing rate to detect the disturbance starting point, and then utilizes an improved empirical mode decomposition (EMD) to obtain the effective time-frequency distribution of the extracted signal. In the end, a cross correlation is used to estimate the time delay of the effective extracted signal. The scheme is also verified and analyzed experimentally. The field test results demonstrate that the proposed scheme can achieve a detection of 96.60% of positioning errors distributed within the range of 0~±20 m at the sensing length of 75 km, which significantly improves the positioning accuracy for the long range asymmetric fence perimeter application.**

Index Terms—**Fiber optic distributed sensor, Asymmetric dual Mach–Zehnder interferometer (ADMZI), positioning algorithm, signal analysis, Empirical mode decomposition (EMD).**

I. Introduction

As a new type of passive distributed sensing system distributed fiber optic sensing system is widely used in long-distance pipelines invasion, leak detection, border security, and other fields, etc. [1-8]. With the rapid development of optical fiber sensing technology, fiber security systems have been generated based on dual Mach-Zehnder interferometry (DMZI) vibration detection. Compared with the traditional security systems, the security system based on DMZI has the advantages of high sensitivity, anti-electromagnetic interference and low loss, etc. The key technology of obtaining disturbance position in Asymmetric Dual Mach-Zehnder Interferometer (ADMZI) systems is the positioning algorithm. Currently many cases have been reported regarding the positioning accuracy of the DMZI.

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Yang An *et al*. proposed the use of cross-correlation function to estimate the arrival time difference of the two channels disturbance signals, together with applying simulated annealing as the control algorithm to reduce the locating error, which was not only complex to operate and difficult to implement, but also increased the cost of the system [9]. One study by Q. Chen *et al*. significantly improved the computational speed by using the zero-crossing method for detecting vibration starting point and extracting effective data components before the general cross-correlation function. Although the positioning accuracy is 20m, the range is not large enough in some place [6]. Xie *et al*. used a Butterworth high-pass filter (HPF) to broaden the 3-dB bandwidth of the power spectrum of interference signal, and achieved a smaller locating mean square error (MSE) in the system [5], [10]. Although Xie's algorithm analyzed and reduced the positioning error of DMZI sensor, it ignored the environment noise in the perimeter security.

In order to solve the problems existing in the current equipment such as large positioning error, this paper theoretically analyzes the positioning error of the ADMZI sensing system. Based on the analysis of the theory, we propose an improved positioning algorithm with a low positioning error. Firstly, we achieve endpoint detection with the highest zero-crossing rate (ZCR) as the ZCR is easy and efficient to implement [11], [12]. Meanwhile, in order to obtain a valid signal disturbance and to reduce the computation time, we process the signal based on an improved empirical mode decomposition (EMD) method [13] which uses the correlate coefficient significant test to discard the low test value intrinsic mode function (IMF) components and reconstructs the rest of the signal. Finally, cross correlation is used to estimate the time delay based on the reconstructed signals [14], [15]. Compared to the other reported positioning algorithms, experimental results verify that our scheme has improved a higher positioning accuracy and achieved a smaller positioning error.

II. Schematic of the ADMZI Vibration Sensor and Positioning principle

The structure of an ADMZI by using two DFB (distributed feedback) lasers and matching DWDM (dense wavelength division multiplexing) [16] is shown in Fig. 1, where the two outputs of the lasers (λ_1 and λ_2) are equally split by couplers C2 and C3, respectively, then λ_1 and λ_2 propagate in opposite directions in the ADMZI. In clockwise (CW) MZI, the λ_1

interfere with itself at the C3 after being split by C2. The propagation path of the λ_1 passes though C1-C2-C3-C4, and is filtered by DWDM1 and detected by PD2 (photo-detector). As DWDM2 can remove the C-RB (clockwise propagated Rayleigh backscattering wave) noise of λ_2 and let the C-PW (clockwise propagated primary wave) of λ_1 go through perfectly, we can easily acquire the signal of C-PW with a high SNR (signal to noise ratio). Here we use two different wavelengths of λ_1 and λ_2 as the sources that are close to 1550 nm, and the difference between λ_1 and λ_2 are larger than the window separation of 0.8 nm. PC1 (polarization controller) and PC2 are used to compensate the visibility variation in each MZI. The situation in the counter-clockwise (CCW) direction MZI is the same.

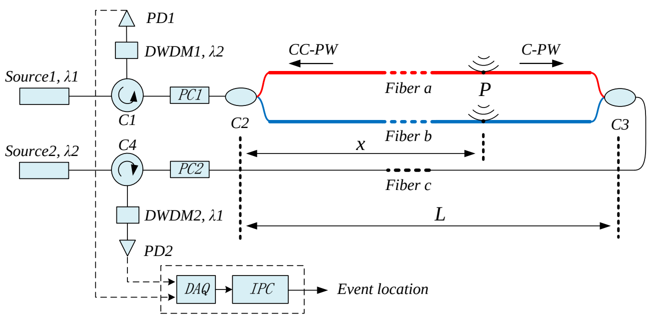

Fig.1. Schematic diagram of ADMZI disturbance sensing system. C2, C3: 3dB fiber coupler; C1, C4: Optical circulator; PD1, PD2: Photo-detector; PC1, PC2: Polarization Controller; DWDM1, DWDM2: dense wavelength division multiplexers; DAQ: Data Acquisition Card; IPC: Industrial Personal Computer; C-PW, CC-PW: the clockwise and counter-clockwise propagated primary wave.

Assume that a disturbance is suited at a distance of *x*. From Fig.1, we can see that the time delay *d* between the distances from *P* to PD1 (CCW) and from *P to* PD2 (CW) is usually different. The time difference *d* can be calculated as:

$$d = n \times (L - 2x) / c \qquad (1)$$

Where *c* is the velocity of lightwave in vacuum (3×10^8 *m/s*), *n* is the effective refractive index of fiber optic core, *L* is the length of the test cable. Here, *c*, *n* and *L* are all constant. From equation (1), we can deduce the disturbance position *x* from the time delay *d*.

However, there are different kinds of noises in ADMZI in practical applications, the AC components of the received noise-involved interference signal can be expressed as [5], [6]:

$$\begin{cases} I_1(t) = [1+n_{a1}(t)]\cdot\cos[2\pi\times\dfrac{l(t)}{\lambda_2}+\xi_1(t)+n_{\varepsilon1}(t)+n_{p1}(t)]+n_{b1}(t)+n_{c1}(t) \\ I_2(t) = [1+n_{a2}(t)]\cdot\cos[2\pi\times\dfrac{l(t-d)}{\lambda_1}+\xi_2(t)+n_{\varepsilon2}(t)+n_{p2}(t)]+n_{b2}(t)+n_{c2}(t) \end{cases} \qquad (2)$$

Where *l(t)* is the OPD (optical path difference) generated by vibration, λ_1 and λ_2 are the wavelengths of source1 and source2 in the two MZIs. Polarization effect induces the visibility noise $n_{a1}(t)$, $n_{a2}(t)$ and the visibility noise $n_{\varepsilon1}(t)$, $n_{\varepsilon2}(t)$. The slight vibration induces the additional environment noise $\xi_1(t)$ and $\xi_2(t)$ in the system. $n_{p1}(t)$ and $n_{p2}(t)$ are the phase noise introduced by the frequency noise of the laser source, $n_{c1}(t)$ and $n_{c2}(t)$ are the additive circuit noise, respectively, $n_{b1}(t)$ and $n_{b2}(t)$ are the back-scattering noise coming from the mixture of interference signals between CC-RB in fiber *a* and *b* as well as the interference between CC-RB and CC-PW in the coherence area.

According to the above analysis, the use of model (1) will lead to an inaccurate time difference *d* only with a simple cross correlation function. Thus we can add a restriction and make an assumption to solve this issue.

Restriction: In order to assure that the $\xi_1(t)$ and $\xi_2(t)$ are almost constant during the time of experiment, we set each duration of experiment to a small value.

Assumption: The additive circuit noises $n_{c1}(t)$ and $n_{c2}(t)$ can be regarded as white noise with small amplitude.

On the basis of the above restrictions, as the $n_{p1}(t)$ and $n_{p2}(t)$ can be reduced by utilizing a narrow line-width laser and compensating the length difference between the two interferometer arms, we can neglect the phase noise. The effect of additive circuit noises $n_{c1}(t)$ and $n_{c2}(t)$ can also be neglected. Similarly, we can also adjust polarization state of the light to compensate $n_{a1}(t)$ and $n_{a2}(t)$, $n_{\varepsilon1}(t)$ and $n_{\varepsilon2}(t)$ [17-19]. Although the sensing range is long, the SNR still stays high and therefore RB noise $n_{b1}(t)$ and $n_{b2}(t)$ cannot be neglected [19]. Besides, we can easily suppress the RB noise and acquire the signal of CC-PW with a high SNR in the ADMZI structure [16].

Therefore, the alternating current components of the two output signals can be simplified as:

$$\begin{cases} I_1(t) = \cos[2\pi\times\dfrac{l(t)}{\lambda_2}+\xi_1(t)] \\ I_2(t) = \cos[2\pi\times\dfrac{l(t-d)}{\lambda_1}+\xi_2(t)] \end{cases} \qquad (3)$$

From the equation (3), we can see $I_1(t)$ and $I_2(t)$ are cosine functions. *l(t)* and *l(t-d)* are both functions depending on time *t* only. So, the frequencies of $I_1(t)$ and $I_2(t)$ are proportional to the frequencies of *l(t)* and *l(t-d)* respectively. We can utilize the time-frequency distributions for the $I_1(t)$ and $I_2(t)$ instead of *l(t)* and *l(t-d)* to compute the time delay *d*. $\xi_1(t)$ and $\xi_2(t)$ are constant.

III. Principle of the Proposed Positioning Algorithm

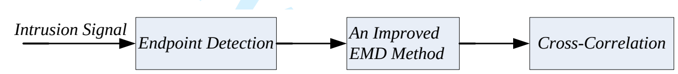

Fig.2. Framework of position algorithm.

Fig. 2 shows the consequence frame of the positioning algorithm. Firstly, we extract the endpoint of the disturbance signal based on zero-crossing technique. Then we use the improved empirical mode decomposition (EMD) method to discard the low test value IMF components and to reconstruct the rest of the signal. Finally, the cross correlation is used to estimate the time delay using the reconstructed signals.

A. *Endpoint detection based on ZCR*

ZCR is usually applied to discrete-time signals such as distinguishing the sounds of different frequencies [12]. ZCR can be expressed as:

$$ZCR_n = \sum_{-\infty}^{\infty} \left| \operatorname{sgn}[x(m)] - \operatorname{sgn}[x(m-1)] \right| \omega(n-m)$$
$$\text{where} \quad \operatorname{sgn}[x(n)] = \begin{cases} 1 & x(n) \geq 0 \\ -1 & x(n) < 0 \end{cases}$$
$$\text{and} \quad \omega(n) = \begin{cases} 1/2N & 0 \leq n \leq N-1 \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

Note that N is the length of a selected frame. *sgn[x]* is a symbolic function. $\omega(n)$ is a rectangular window function. The principle of signal interception based on ZCR is: the undisturbed signal or noise signal differs from the disturbance signal in frequency domain so that the ZCR of disturbance signal is higher than that of the undisturbed signal or noise signal. Therefore we can pull out the disturbance signal from the undisturbed signal or noise signal easily. In order to improve the robustness of ZCR, it also needs to meet the requirement that vibration amplitude should exceed a certain threshold when the signal is calculated through ZCR. Signal higher than the threshold signal segment is identified as disturbing signal; on the contrary, signal lower than the threshold is regarded as the noise signal or interference signal.

In order to fulfill the assumption and locate the zero-crossing point, we apply the double-threshold crossing method to eliminate the additive circuit noises. As the threshold might truncate the discrete-time signals if the differences between the threshold and successive samples have different algebraic signs. We set the two thresholds as δ_1 and δ_2, where $\delta_1>0$, $\delta_2<0$, and $|\delta_1|=|\delta_2|$. We note that, in order to eliminate the effect of additive circuit noises, the value of $|\delta_1|$ should be larger than the amplitudes of noise.

And we note that if a point is a zero crossing, it must meet three conditions:

1) The amplitude of the point Z_k $(k=1,2,3\cdots K)$ is zero.
2) The product of the amplitude of Z_{k-1} (which is before Z_k) and Z_{k+1} (which is after Z_k) is less than zero.
3) The amplitudes of Z_{k-1} and Z_{k+1} cross over the two thresholds δ_1 and δ_2 respectively.

When a point meets the above three conditions at the same time, it can be located as one zero-crossing point. Then we can obtain the endpoint of the disturbance signal from the maximum zero-crossing.

B. An improved EMD method

The empirical mode decomposition is a self-adaptive decomposition method based on the local characteristics of the signal, which can effectively decompose the original time-domain signal into the intrinsic mode function with multi-scale time-frequency characteristics. EMD is usually applied to non-linear and non-stationary processes [20].

Obviously, the disturbance signal of a long range asymmetric perimeter security system is an unsteady signal, which can be decomposed into a collection of IMF components. Each IMF should meet two conditions: (1) in the whole data set, the number of extrema and the number of zero-crossings must either equal or at most have one difference; (2) at any point, both the mean value of the envelope defined by the local maxima and the envelope defined by the local minima are zero.

The correlate coefficient is the most common measurement to evaluate the correlation between variables. Generally speaking, the small correlate coefficient means the low correlation between the variables; and vice versa. However, the increase in the length of signals makes the correlate coefficient become lower and the error get larger. Therefore it is obviously inaccurate to only apply the correlate coefficient to evaluate the correlation between investigated signals. Alternatively, we apply t test which is one of the significant test of correlate coefficient to evaluate the significant of correlate coefficient between the concerned signals based on statistics principles [21]. The steps of the significant test are following:

1) Decompose the vibration signal into a collection of IMFs c_i $(i= 1,2,3\cdots M)$. Calculate the correlate coefficient ρ_i for each IMF component with the original signal by formula (5):

$$\rho_i = \frac{\sum_{j=1}^{R}(c_{ij} - \overline{c_i})(x_j(t) - \overline{x(t)})}{\sqrt{\sum_{j=1}^{R}(c_{ij} - \overline{c_i})^2 \sum_{j=1}^{R}(x_j(t) - \overline{x(t)})^2}} \tag{5}$$

Where the i *th* is the IMF component. M is the number of the IMF components. R is the total number of points.

2) The t test value of the correlate coefficient ρ_i is expressed as:

$$t_i = \frac{\rho_i \sqrt{R-2}}{\sqrt{1-\rho_i^2}} \tag{6}$$

3) Check the t distribution table to obtain the critical value $t_{\alpha/2}$ based on the given significance level α and freedom degrees *(R-2)*. If $|t_i| < t_{\alpha/2}$, ρ_i is considered to be insignificant in statistics, therefore the corresponding IMF components will be eliminated. Otherwise, it is considered to be significant, and corresponding IMF components will be reserved.

Reconstruct the remaining IMF components after sweeping t distribution, and we can obtain the time-frequency information of the disturbance signal.

C. Time delay estimation based on cross-correlation

Assuming that the correlated noises are stationary in a short period, we can directly estimate the time delay between the selected signals after obtaining time-frequency information of the disturbance signal. The time delay estimation based on the cross-correlation signal - noise model is [22]:

$$\begin{cases} I_1(t) = s(t) + n_1(t) \\ I_2(t) = s(t+\tau) + n_2(t) \end{cases} \tag{7}$$

Where $s(t)$ is the delay signal, $n_1(t)$ and $n_2(t)$ are the additive white Gaussian noise. Assuming that $s(t)$, $n_1(t)$, $n_2(t)$ are zero-mean random stationary process, and $s(t)$, $n_1(t)$, $n_2(t)$ are independent, the cross-correlation function between them is approximately zero. After $I_1(t)$ and $I_2(t)$ calculated based on cross-correlation, we can have:

$$\begin{aligned} R_{I_1 I_2}(t) &= R_{ss}(t+\tau) + R_{s_1 n_2}(t) + R_{s_2 n_1}(t) + R_{n_1 n_2}(t) \\ &\approx R_{ss}(t+\tau) \end{aligned} \tag{8}$$

Where $R_{ss}(t+\tau)$ is the autocorrelation function of *s(t)*. According to the nature of the autocorrelation function, when $t=-\tau$, we can obtain the maximum of autocorrelation function. Therefore the time delay *d* can be estimated by locating the peak position of cross-correlation function $R_{I_1 I_2}(t)$.

IV. Field Experiments and Analysis

The practical experiment setup is shown in Fig 1. The length of the sensing cable is 75 km with single mode fibers. The two laser sources λ_1 and λ_2 are 1549.95nm and 1550.74nm distributed feedback laser respectively with a power of 5 mW and a line-width of 50 kHz (corresponding to the coherence length of 6 km). The central wavelengths of DWDM1 and DWMD2 are 1550.12 nm and 1550.92 nm respectively and with the pass-band width of ±0.22 nm to match λ_1 and λ_2. The two light beams propagate CW directions (C1-C2-C3-C4) and CCW directions (C4-C3-C2-C1) respectively. The synchronous sampling rate of DAQ card and the sampling time of a frame signal are set to be 10 MS/s and 0.3 s respectively. We have conducted 500 sets of in-field experiments in the system, the intrusion is generated at the distance x = -45041m by knocking the fence.

A. Endpoint detection

Firstly, we obtain the endpoint of the vibration signal based on ZCR after the vibration signal is noise-filtered. The vibration signal of knocking cable and disturbance extraction section are shown in Fig. 3 (b). And Fig. 3 (c) shows the zero-crossing rate distribution of the vibration signal.

Fig. 3(a) and (b) show the interference signals and undisturbed signal. From the figures, it can be seen that the phase change induced by the intrusion event varies much more fiercely than the environment noise. We can also see different signal densities at different time periods, and the output intrusion signal shows great irregularity. Besides, the large amount of acquisition points will lead to a long time operation if signal is decomposed by EMD subsequently. It is important for selecting a valid signal region.

From Fig. 3 (c) we can obtain the distribution of the disturbance signal and easily find the peak position of the curve. On the basis of the positioning theory [6], a high ZCR of the signal segment means a large bandwidth with high positioning accuracy. Therefore we detect the peak position of the ZCR curve and extract 50k samples which are around the peak as the effective signal region.

B. An improved EMD method

From Fig. 4 we can see the vibration signal is decomposed into IMF components by empirical mode decomposition. The disturbance signal can be expressed as:

$$x(t) = \sum_{i=1}^{M} c_i(t) + r_M(t) \tag{9}$$

From Fig. 4 we can visually see that although each IMF component is decomposed by the original signal, the relevance between each IMF component and the original signal is different, therefore, the redundant IMF components with a low

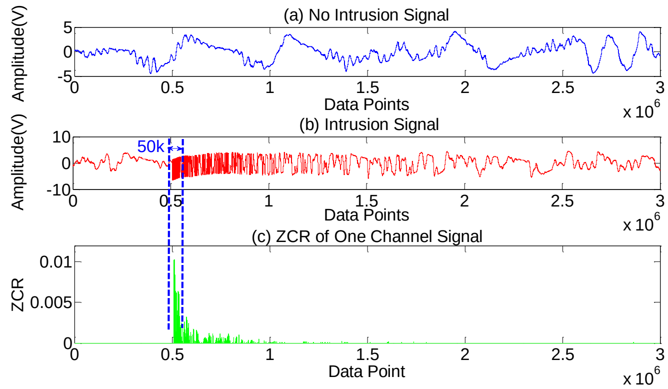

Fig. 3. Undisturbed signal and interference signals. (a) No intrusion. (b) Knocking cable. (c) ZCR of the knocking cable.

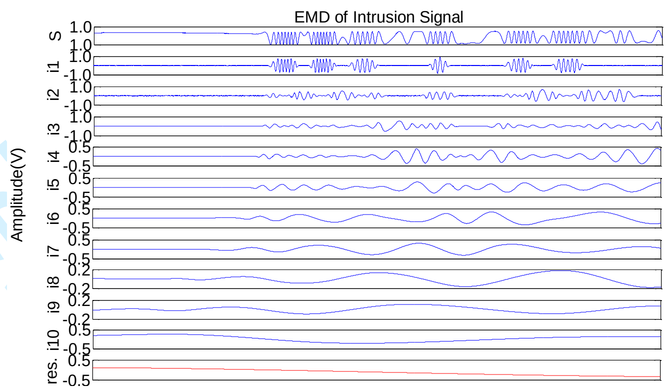

Fig. 4. EMD decomposition.

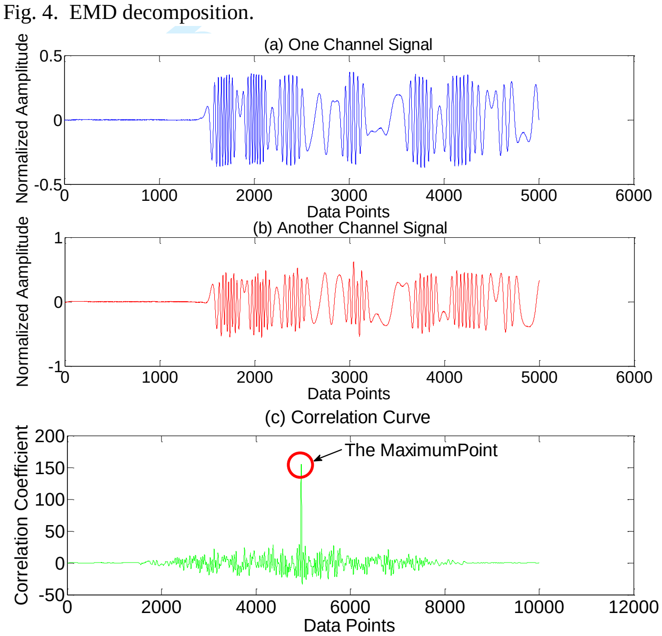

Fig. 5. Reconstruct the signal. (a) One channel signal. (b) Another channel signal. (c) Correlation coefficient of the two channel signal.

correlation can be removed.

According to (5), (6), the absolute value of the t test $|t_i|$ and the correlation coefficients ρ_i of each IMF are shown in Table I.

TABLE I
CORRELATE COEFFICIENT AND ABSOLUTE VALUE OF T-DISTRIBUTION TEST.

IMFs	ρ_i	$\|t_i\|$
IMF1	0.496	40.402
IMF2	0.388	29.768
IMF3	0.327	24.462
IMF4	0.329	24.652
IMF5	0.231	16.743
IMF6	0.226	16.366
IMF7	0.144	10.317
IMF8	0.127	9.058
IMF9	0.020	1.379
IMF10	-0.014	1.003
res	0.376	28.651

We set α to 0.05, $R-2=4998$ and get $t_{\alpha/2}=1.9604$ by checking the t-distribution table. Comparing $|t_i|$ to the t-distribution at $t_{\alpha/2}=1.9604$, if the former is larger, the corresponding IMF components is retained, otherwise is discarded. Here we eliminate IMF9, IMF10 and reserve the rest. Finally, we reconstruct the disturbed signal by preserving IMF components to obtain the time-frequency information of the disturbed signal, which is shown in Figure 5 (a), (b).

C. Location based on cross-correlation

After reconstructing the disturbed signal based on the improved EMD method we can get time-frequency information of the disturbed signal. And then the correlation curve of the two channel signal is obtained, which is shown in Fig. 5 (c). From Fig. 5 (c), we can obtain the time delay estimation by simply using the cross-correlation algorithm.

As a comparison, the experiment based on endpoint detected and cross-correlation (ZCR-CC) without EMD is also conducted. TABLE II shows position error statistics of 500 sets experiments using the proposed method and ZCR-CC without EMD method.

TABLE II
COMPARISON OF POSITIONING ERROR STATISTICS BETWEEN THE PROPOSED METHOD AND ZCR-CC WITHOUT EMD METHOD

Method	Mean absolute error(MAE/m)	Standard deviation(SD/m)
Proposed Method	4.7360	7.7376
ZCR-CC without EMD	31.1622	52.3317

From the TABLE II, compared to ZCR-CC without EMD (MAE =31.622 m, SD =52.3317 m), the proposed method (MAE = 4.7360 m, SD = 7.7376 m) can significantly reduce the SD and MAE of the location error, and can improve the positioning accuracy in the long range asymmetric fence perimeter system.

According to the experimental results, we can see that the proposed method can detect up to 96.60% of positioning errors distributed within ±20m. Especially, 84.80% of the location error distributes within ±10 m can be detected, which is very close to the theoretical precision limit. That means that only a minor part of error is outside the range of ±20 m.

V. CONCLUSIONS

This paper proposes an improved positioning algorithm in long range ADMZI vibration sensors. We have theoretically analyzed the principle of the positioning in the long range optical fiber perimeter security system by taking into account all types of noises. According to the theoretical analysis, we applied ZCR to extract the endpoint of the intrusion signal. Then we used an improved EMD method to eliminate low redundant IMF components and to obtain a valid signal disturbance. Finally, the cross correlation function was used to estimate the time delay of the reconstructed signals. The field experiments demonstrate that the proposed approach can achieve the detection of 96.60% of positioning errors distributed within the range of 0~±20 m at the sensing length of 75 km, which has a good potential in practical long range asymmetric perimeter security systems.

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