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# A Study on Autonomous Integrity Monitoring of Multiple Atomic Clocks

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Abstract: A stable and reliable time keeping system depends on the integrity monitoring of the atomic frequency standard. This paper reports a scheme for autonomous integrity monitoring of multiple atomic clocks, which combines the frequency standard comparison method and the frequency jump detection method. The frequency standard comparison method uses multi-channel synchronous acquisition technology and digital frequency measurement technology to realize the precise measurement of multiple atomic frequency standards. The frequency jump detection method uses adaptive filtering to predict the relative frequency difference and give an accurate and timely alarm for the abnormal of frequency jump. The results show that the noise floor frequency standard comparator is better than $6.5\times10^{-15}$ s. For a relative frequency deviation of $2.0\times10^{-6}$ Hz, the probability of anomaly detection is almost 100 %. The system has high frequency measurement resolution and fast alarm of frequency jump, which can meet the real-time requirements of a time keeping system for the integrity monitoring of multiple atomic clocks.

Keywords: Autonomous integrity monitoring, frequency standard comparison, frequency jump detection, noise floor.

## 1. INTRODUCTION

In the fields of modern industrial production, scientific research, civil economy, such as power communication, geodesy, satellite navigation, transportation, etc., the high-precision atomic clock provides an accurate time-frequency reference for them. In the global satellite navigation system (GNSS), the accuracy of satellite navigation and positioning mainly depends on the performance of on-board atomic clocks [1]-[3]. For example, the "nanosecond" time deviation of GPS navigation satellite system will directly cause the "meter" positioning error of users [4]. In addition, the atomic clock is also an important part of the laboratory timekeeping system. Modern timekeeping systems mostly provide time-frequency reference in the form of an atomic clock group. Although the frequency accuracy and frequency stability of the atomic clock are very high, due to the factors such as the aging of components and changes in the operating environment, the output signal of the atomic clock may be abnormal. Therefore, in order to ensure the reliability and effectiveness of time reference, whether it is navigation satellite or laboratory timekeeping system, it is of great significance to monitor the integrity of atomic clock output signal in real time.

Frequency jump is the most common anomaly. The detection of the frequency jump anomaly of atomic clock is very important. It requires that the detection must be fast. The higher the detection probability (PD) and the lower the false alarm probability (PFA), the more reliable the time keeping system can be. The fast detection of frequency jump anomaly requires the frequency measurement of multiple atomic clock signals to be synchronized and real-time. In addition to the influence of the performance of the frequency jump detection algorithm, the resolution of the frequency jump anomaly detection also depends on the measurement resolution of the frequency measurement system. Although there are many excellent frequency jump detection algorithms [5]-[7], there is no comprehensive and detailed solution for autonomous integrity synchronous monitoring about multiple atomic clocks in the time keeping system, and it also cannot locate the abnormal signals autonomously.

To realize the synchronous and real-time monitoring of multiple atomic clocks, and locate the abnormal atomic clocks, an autonomous integrity monitoring method of atomic clock group is proposed in this paper. Firstly, the scheme design of an autonomous integrity monitoring system is given. Secondly, the frequency comparison measurement algorithm is introduced in detail. Then the integrity monitoring algorithm is given to monitor the frequency jump. Simultaneously, the effectiveness of the algorithm is verified by simulation. Ultimately, we analyze the results, and the discussion is given.

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## 2. AUTONOMOUS INTEGRITY MONITORING SCHEME

To ensure the accuracy of fault discrimination and the timeliness of alarm, the scheme of autonomous integrity monitoring of atomic clocks shown in Fig.1. is given in this paper.

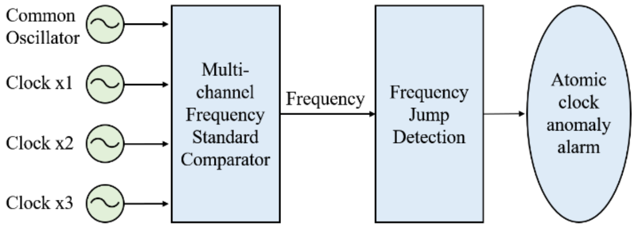


Fig.1. The scheme of autonomous integrity monitoring of atomic clocks.

The multi-channel frequency standard comparator supports synchronous measurement of four channels signal with a nominal frequency $f_0$ = 10 MHz. One of the input channels is a common oscillator, which is used to compare with other measured atomic clock signals to alarm the abnormal atomic clock. The multi-channel frequency standard comparator measures the relative frequency difference between the input signal and the common oscillator every second. The frequency jump detection module analyzes the frequency relative frequency difference to determine whether frequency jump abnormality occurs. Finally, the atomic clock abnormal alarm module judges the abnormal attribution of the atomic clock by analyzing the abnormal conditions from relative frequency difference. The proposed scheme can not only achieve high-resolution measurement of the frequency of multiple atomic clock signals, but also ensure the real-time and effectiveness of anomaly monitoring.

## 3. FREQUENCY STANDARD COMPARISON METHOD

With the development of science and technology, the performance of atomic frequency standards is constantly improving. For example, the frequency fluctuation range of cesium atomic clocks reaches $10^{-12}$@10 MHz and the frequency fluctuation range of hydrogen atomic clock reaches $10^{-13}$@10 MHz or even smaller, which puts forward higher requirements for the measurement resolution of atomic frequency standard measurement equipment to achieve high-precision abnormal monitoring of frequency jump.

Aiming at the high-precision abnormal monitoring of frequency jump from multiple atomic clocks, a multi-channel frequency standard comparison method based on digital measurement of beat signal is proposed. This method uses the multi-channel synchronous acquisition technology and digital frequency measurement algorithm to measure the frequency of input signals. Fig.2. shows the schematic diagram of the multi-channel frequency standard comparison.

The common oscillator provides a reference for the frequency offset generator (FOG) to synthesize a frequency offset signal with a deviation $f_b$ from the nominal frequency $f_0$. The common oscillator and each atomic clock signal are mixed with the frequency offset signal, respectively. After low-pass filtering, a sinusoidal beat signal with frequency $f_b$ is generated. The analog-to-digital convertor of each channel uses a common sampling clock to ensure the synchronization of frequency measurement results. Finally, the amplitude of each beat signal and the frequency deviation of each atomic clock signal relative to the common oscillator are calculated by using the digital frequency measurement algorithm.

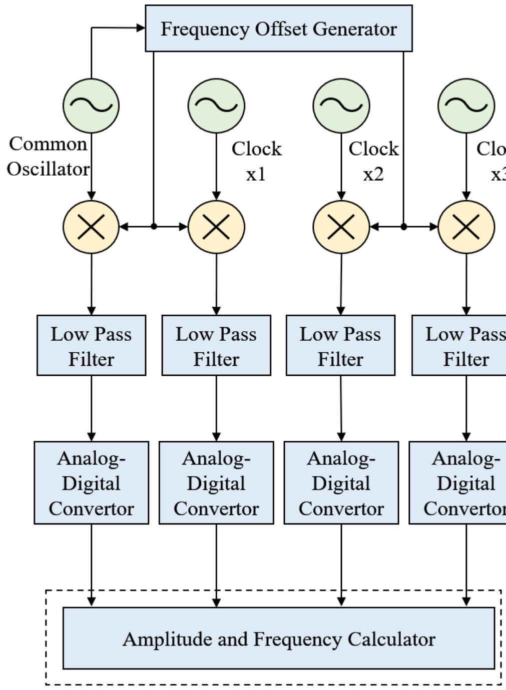


Fig.2. Schematic diagram of multi-channel frequency standard comparison.

### A. *Digital frequency measurement algorithm*

The sinusoidal beat signals at the $j$ and $j$+1 second of channel $i$($i$ = 1,2,3,4) can be expressed as follows:

$$S_{i,j}(n) = V_{i,j}\, sin\left[2\pi\left(\frac{f_b+\Delta f_{i,j}}{f_s}\right)n + \varphi_{i,j}\right] + N_{i,j}(n),\quad n \in [1, f_s] \tag{1}$$

$$S_{i,j+1}(n) = V_{i,j+1}\, sin\left[2\pi\left(\frac{f_b+\Delta f_{i,j}}{f_s}\right)n + \varphi_{i,j+1}\right] + N_{i,j+1}(n),\quad n \in [f_s+1, 2f_s] \tag{2}$$

where $f_s$ denotes the sampling rate of the analog-to-digital conversion. $V_{i,j}$ and $V_{i,j+1}$ denote the amplitude of the sinusoidal beat signal. $f_b$ is the frequency of the sinusoidal beat signal and its value is 1 Hz. $\Delta f_{i,j}$ is the frequency deviation relative to the nominal frequency $f_b$. $N_{i,j}$(n) and $N_{i,j+1}$(n) are Gaussian white noise superimposed on the signal, $n$ denotes the discrete time.

The cross-correlation results of $S_{i,j}$(n) and $S_{i,j+1}$(n) are as follows:

$$R_{S_{i,j},S_{i,j+1}}(\tau) = \frac{1}{N}\sum_{n=0}^{f_s-1} S_{i,j}(n)\, S_{i,j+1}(n+\tau) = \\ = \frac{1}{2}\, V_{i,j}V_{i,j+1}cos\left[2\pi\left(\frac{f_b+\Delta f_{i,j}}{f_s}\right)\tau + \Delta\phi\right] + \\ + R_{S_{i,j},N_{i,j+1}} + R_{S_{i,j+1},N_{i,j}} + R_{N_{i,j},N_{i,j+1}} \tag{3}$$

where $\tau$ denotes the delay of correlation operation, $\tau$ is a discrete integer variable whose value is [-$f_s$, $f_s$-1]. $\Delta\phi = \varphi_{i,j+1} - \varphi_{i,j}$ represents the initial phase difference. Since the signal and noises are not correlated, the noises are not correlated with each other, or the correlation is small enough to be ignored, then the cross-correlation equation $R_{S_{i,j},N_{i,j+1}} = R_{S_{i,j+1},N_{i,j}} = R_{N_{i,j},N_{i,j+1}} = 0$ is satisfied.

When the $\tau = 0$, formula (3) can be expressed as:

$$R_{S_{i,j},S_{i,j+1}}(0) = \frac{1}{2}V_{i,j}V_{i,j+1}\cos(\Delta\phi) \tag{4}$$

$S_{i,j}$(n) and $S_{i,j+1}$(n) perform a cross-correlation operation with themselves, respectively, to obtain the amplitude of the beat signal as follows:

$$V_{i,j+1} = \sqrt{2R_{S_{i,j+1},S_{i,j+1}}(0)} \tag{5}$$

$$V_{i,j} = \sqrt{2R_{S_{i,j},S_{i,j}}(0)} \tag{6}$$

According to formulas (4)-(6), the $\Delta\phi$ can be expressed as:

$$\Delta\phi = \pm\, arccos\left(\frac{R_{S_{i,j},S_{i,j+1}}(0)}{\sqrt{R_{S_{i,j},S_{i,j}}(0)\cdot R_{S_{i,j+1},S_{i,j+1}}(0)}}\right) \tag{7}$$

The initial phase $\varphi_{i,j+1}$ of $S_{i,j+1}$(n) is equal to the phase of $S_{i,j}$(n) at $n = f_s$. As shown in the following:

$$\varphi_{i,j+1} = \varphi_{i,j} + 2\pi(f_b + \Delta f_{i,j}) \tag{8}$$

Since the frequency deviation $\Delta f_{i,j}$ can be divided into integer frequency deviation $\Delta f_{int\_i,j}$ and decimal frequency deviation $\Delta f_{dec\_i,j}$, it is expressed as follows:

$$\Delta\varphi = 2\pi\cdot(f_b + \Delta f_{int\_i,j} + \Delta f_{dec\_i,j}) = 2\pi\cdot\Delta f_{dec\_i,j} \tag{9}$$

Then the decimal frequency deviation $\Delta f_{dec\_i,j}$ is expressed as：

$$\Delta f_{dec\_i,j} = \pm\frac{1}{2\pi} arccos\left(\frac{R_{S_{i,j},S_{i,j+1}}(0)}{\sqrt{R_{S_{i,j},S_{i,j}}(0)\cdot R_{S_{i,j+1},S_{i,j+1}}(0)}}\right) \tag{10}$$

In addition, the fast Fourier transform (FFT) algorithm is used to analyze the power spectrum of the digital sinusoidal beat signal, and solves the integer frequency value of the sinusoidal beat signal.

According to the principle of the dual mixer time difference (DMTD) method [8]-[10], the measured frequency of the sinusoidal beat signal can be divided by a beat factor $f_0/f_b$ to calculate the frequency of atomic clock of each channel.

## 4. FREQUENCY JUMP DETECTION METHOD

The frequency of atomic clock signals, including common oscillator, can be calculated by using a frequency standard comparator. The relative frequency difference between the clock $i$ and common oscillator is $\Delta f_{ic}$. Fig.3. shows the flow chart of the frequency jump detection method.

After caching the relative frequency difference data with length $M$, the adaptive filter predicts the relative frequency difference, i.e., $AFP_{i,c}(M+1)$, based on the $M$ relative frequency difference data measured previously. The predicted value is compared with the measured value. If the frequency jump range exceeds the threshold $G_F$, then we can determine the frequency jump alarm, otherwise the frequency is not abnormal and the measurement can continue.

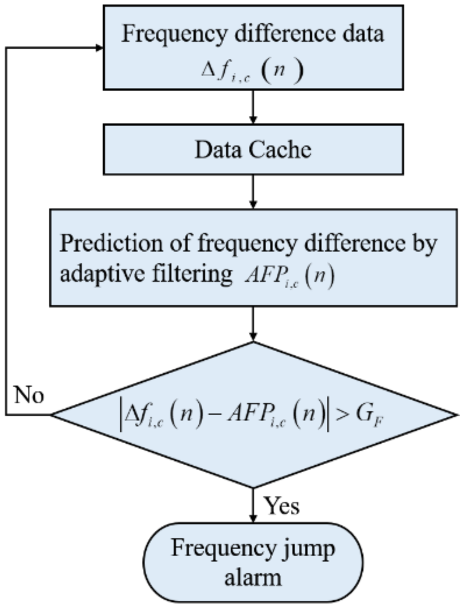


Fig.3. The flow chart of frequency jump detection method.

### A. *Adaptive filter prediction algorithm*

Adaptive filter adjusts its own filter parameters to the best possible level based on the input data. It does not need any prior statistical information about signal and noise [11]. The $M$+1 relative frequency difference can be estimated from the previous $M$ relative frequency difference data, and the expression is as follows:

$$AFP_{i,c}(M+1) = W_M^T X_M \tag{11}$$

where $W_M$ represents the weight coefficient vector at time M and $W_M^T = [w_1, w_2, \cdots, w_M]$. $X_M$ is the input vector at time M and $X_M = [\Delta f_{i,c}(1), \Delta f_{i,c}(2), \cdots, \Delta f_{i,c}(M)]^T$.

The prediction error can be expressed as:

$$e(M) = \Delta f_{i,c}(M+1) - AFP_{i,c}(M+1) \tag{12}$$

When the estimated mean square error $E[e_M^2]$ is minimum, it means that the parameters of the weight coefficient vector $W_M$ are optimal. Then the following equation holds:

$$\nabla = \left[\frac{\partial E[e_M^2]}{\partial w_1}, \frac{\partial E[e_M^2]}{\partial w_2}, \cdots, \frac{\partial E[e_M^2]}{\partial w_M}\right]^T = 0 \tag{13}$$

where $\nabla$ is the gradient vector of $E[e_M^2]$.

According to the random gradient descent criterion, the weight coefficient vector at time $M$+1 is updated as follows:

$$W_{M+1} = W_M + \mu e_M X_M \quad (14)$$

where $\mu$ is the constant of the adjustment step size, which determines the speed of convergence. The range of $\mu$ is $[0, 2/\lambda_{max}]$, $\lambda_{max}$ is the maximum eigenvalue of $R_{XX}$.

The new input vector is updated as follows:

$$X_{M+1} = \left[\Delta f_{i,c}(2), \Delta f_{i,c}(3), \cdots, \Delta f_{i,c}(M+1)\right]^T \quad (15)$$

### B. *The judgment of abnormal attribution*

After the frequency jump is detected, it is necessary to judge which signal is abnormal. The probability of abnormality of multiple atomic clocks at the same time is usually very low. We only consider the discrimination of frequency jump from a single clock. The judgment logic is as follows:

$$\text{Case i: if} \begin{cases} \left|\Delta f_{1,c}(n) - AFP_{1,c}(n)\right| > G_F \\ \left|\Delta f_{2,c}(n) - AFP_{2,c}(n)\right| > G_F \\ \left|\Delta f_{3,c}(n) - AFP_{3,c}(n)\right| > G_F \end{cases}$$

the common oscillator has a frequency jump.

$$\text{Case ii: if} \begin{cases} \left|\Delta f_{1,c}(n) - AFP_{1,c}(n)\right| > G_F \\ \left|\Delta f_{2,c}(n) - AFP_{2,c}(n)\right| < G_F \\ \left|\Delta f_{3,c}(n) - AFP_{3,c}(n)\right| < G_F \end{cases}$$

the clock x1 has a frequency jump.

$$\text{Case iii: if} \begin{cases} \left|\Delta f_{1,c}(n) - AFP_{1,c}(n)\right| < G_F \\ \left|\Delta f_{2,c}(n) - AFP_{2,c}(n)\right| > G_F \\ \left|\Delta f_{3,c}(n) - AFP_{3,c}(n)\right| < G_F \end{cases}$$

the clock x2 has a frequency jump.

$$\text{Case iv: if} \begin{cases} \left|\Delta f_{1,c}(n) - AFP_{1,c}(n)\right| < G_F \\ \left|\Delta f_{2,c}(n) - AFP_{2,c}(n)\right| < G_F \\ \left|\Delta f_{3,c}(n) - AFP_{3,c}(n)\right| > G_F \end{cases}$$

the clock x3 has a frequency jump.

Case i: The selection of frequency jump threshold $G_F$

Threshold $G_F$ determines the effectiveness and reliability of frequency jump detection. In the case of no abnormality, the relative frequency difference data satisfies the probability density distribution function of $P(z_1)$. When there is an abnormality, the relative frequency difference data satisfies the probability density distribution function of $P(z_2)$.

The false alarm probability of frequency jump detection can be expressed as:

$$P_{false} = \int_{G_F}^{+\infty} P(z_1)\, dz_1 \quad (16)$$

The frequency jump detection probability can be expressed as:

$$P_{detection} = \int_{G_F}^{+\infty} P(z_2)\, dz_2 \quad (17)$$

As shown in formula (16), if the $G_F$ is too small, the probability of abnormal false alarm is high, and according to formula (17), if the threshold $G_F$ is large, the probability of abnormal detection is low. In the practical engineering application, it is necessary to select a reasonable $G_F$ to ensure high detection probability and low false alarm probability.

## 5. VERIFICATION AND RESULTS

To evaluate the performance of the autonomous integrity monitoring method for multiple atomic clocks proposed in this article, we create an experiment and software simulation to verify the proposed method.

### A. *Noise floor of frequency standard comparator*

The resolution of the comparison measurement will directly affect the accuracy of the fault judgment. According to the digital frequency measurement algorithm, we have developed a multi-channel frequency standard comparator prototype. An experimental test platform is established to evaluate the noise floor of the prototype. Fig.4. shows the diagram of the experimental test platform.

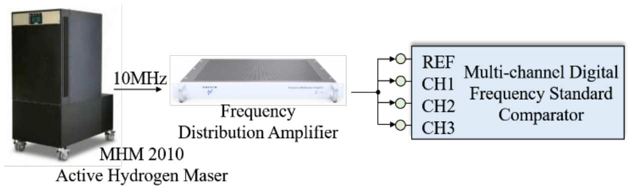


Fig.4. The diagram of the experimental test platform.

A sinusoidal signal generated by an active hydrogen maser is distributed to four channels by the frequency distribution amplifier. Then, four sinusoidal signals are connected to the input port of a multi-channel frequency standard comparator prototype. Fig.5. shows the frequency stability of three measurement channels. For an input signal with the frequency 10 MHz, the noise floor test results of the three measurement channels are $6.26 \times 10^{-15}/s$, $6.19 \times 10^{-15}/s$, $6.10 \times 10^{-15}/s$, respectively, which meets the requirements of high-precision frequency measurement for autonomous integrity monitoring of multiple atomic clocks.

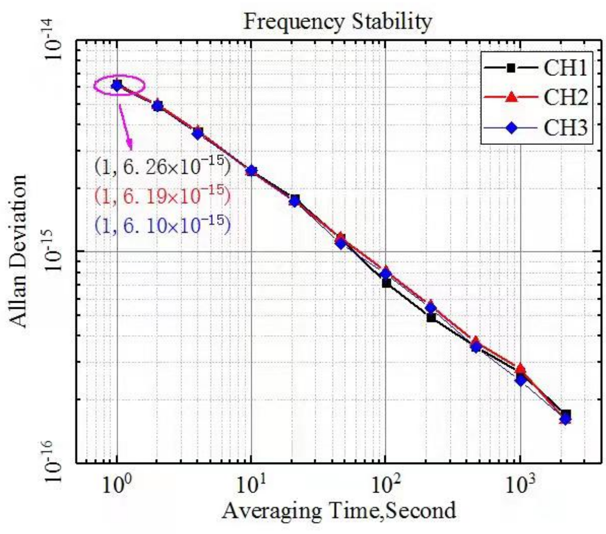


Fig.5. The frequency stability of three measurement channels.

### *B. Simulation of frequency jump detection*

Frequency jump includes instantaneous jump and continuous jump. We select 10000 relative frequency difference data from the noise floor test experiment. As shown in Fig.6.a), a jump at $t = 2000\,s$ with a relative frequency deviation of $2 \times 10^{-6}$ Hz is created to simulate the instantaneous frequency jump, a jump at $t = 6100\,s$ and later with a relative frequency deviation of $5 \times 10^{-6}$ Hz is created to simulate the continuous frequency jump. Fig.6.b) shows the two probability density functions with no frequency jump and continuous frequency jump. The two probability density function curves are extremely narrow, which also reflects the low noise floor of multi-channel frequency standard comparator. According to the probability density function, if the frequency jump threshold is selected as $G_F = 1 \times 10^{-6}$ Hz, the false alarm probability is almost 0 and the anomaly detection probability is almost 100 %.

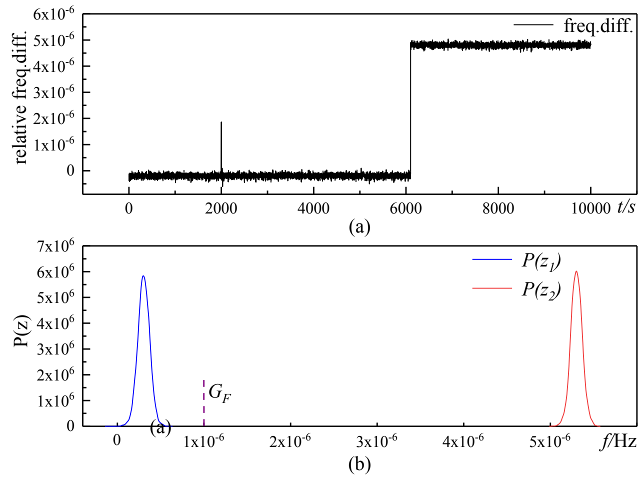


Fig.6. a) frequency difference (freq. diff.) with instantaneous jump and continuous jump. b) The probability density functions with no frequency jump and continuous frequency jump.

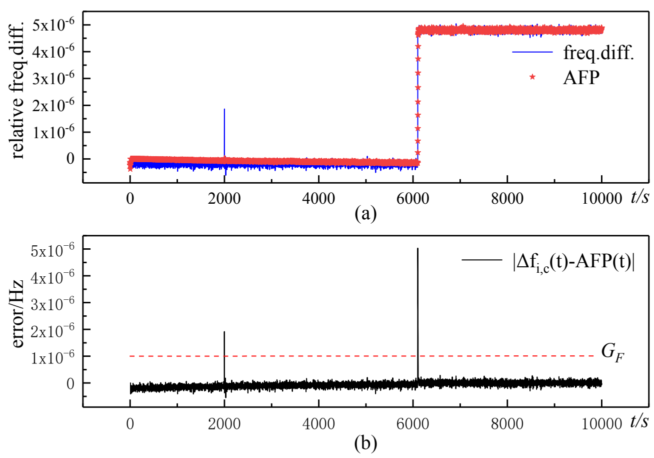


Fig.7. a) The adaptive filtering prediction (AFP) of frequency difference. b) The prediction error of frequency difference.

In the prediction of frequency difference by adaptive filtering, the cached data length $M$ is set to 10, which not only reduces the complexity of mathematical calculation, but also ensures the real-time performance of frequency difference prediction. Fig.7.a) shows the prediction curve of the relative frequency difference by adaptive filtering. The adaptive filter can quickly converge and return to a stable state even if the frequency jump occurs. Fig.7.b) shows the curve of absolute error value. We learned that, both instantaneous frequency jump with a relative frequency deviation $2 \times 10^{-6}$ Hz and continuous frequency jump with a relative frequency deviation $5 \times 10^{-6}$ Hz can be detected rapidly.

## 6. CONCLUSION

The autonomous integrity monitoring of multiple atomic clocks is related to the reliability and effectiveness of the time reference signal provided by the timekeeping system. This study proposes a system of autonomous integrity analysis for atomic clocks, which not only achieves high-resolution measurement of multiple atomic frequency standards, but also monitors the frequency jump abnormality of each atomic frequency standard, and accurately and timely gives a location of abnormal signal.

The noise floor of the multi-channel frequency standard comparator is better than $6.5 \times 10^{-15}/s$, which meets the requirement of frequency measurement resolution for autonomous integrity monitoring of atomic clock. The frequency jump detection algorithm is not only fast and accurate for abnormal alarms, but also can identify a relative frequency deviation of $2 \times 10^{-6}$ Hz, which is enough to meet the frequency monitoring of the clock group composed of hydrogen atomic clock and cesium clock.

The high-resolution frequency measurement of the multi-channel frequency standard comparison method and the real-time alarm of anomaly detection are of great significance in engineering application.

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