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Research on Dynamic Steering Method of Atomic Clock Based on Residual Correction

[1, 2, *] Yuwei Li, [1, 2] Wenli Wang, [1, 2] Yanrong Xue, [1, 2] Ruiqiong Chen and [1, 2] Ya Liu

[1] National Time Service Center, Chinese Academy of Sciences, China
[2] Key Lab. of Time & Frequency Primary Standards, Shaanxi, China
[1] Tel.: + (086)83890447, fax: (086)83890326
E-mail: liyuwei9999@163.com

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Abstract: Precision time-frequency signal generation and maintenance technology is an important foundation of navigation and positioning, which provides actual physical signal and precise time scale for navigation and positioning. In order to generate and maintain the frequency accuracy, frequency stability and synchronization accuracy of time-frequency signals, combined with the characteristics of atomic clock, a method of dynamic atomic clock control by residual correction is proposed. The method greatly improves the frequency accuracy and long-term frequency stability of signals without destroying the short-term stability. The result of synchronization is at least twice as much as that of traditional methods.

Keywords: Precision time-frequency signal, Dynamic atomic clock control, Residual correction, Signal maintenance technology, Minimum control strategy control technology.

1. Introduction

Precision time-frequency signal generation and maintenance technology is an important foundation of navigation and positioning, which provides actual physical signal and precise time scale for navigation and positioning. The performance of time-frequency signal directly affects the positioning accuracy and timing precision of navigation and communication systems.

Frequency deviation and frequency drift exist in the output signal of the free-running atomic clock, which results in the decrease of frequency accuracy, stability and synchronization accuracy. Therefore, it is necessary to control the atomic clock so as to stabilize the output signal of the atomic clock in a certain range and achieve high-precision synchronization.

This paper mainly studies the high precision time synchronization method of atomic clock. The precise time difference prediction method based on least square method, Kalman filter and the other control method of atomic clock are deeply analyzed. Combined with the characteristics of atomic clock, a method of dynamic atomic clock control by residual correction is proposed. The method uses the residual for correcting time difference model to improve the prediction accuracy. When the reference is available, the parameters, such as the attenuation factor and control period, are adjusted according to the time difference prediction in real time; when the reference is not available, an atomic clock autonomous maintenance algorithm is designed to keep the signal synchronized without the assistance of reference source from atomic clock or some external signal.

2. Main Steering Method

Usually, the atomic clock is used to generate high-precision time-frequency signals and system time. Due to the frequency deviation and frequency drift of the freely running atomic clock, the frequency accuracy of the output signal decreases. Therefore, the atomic clock needs to be controlled to stabilize the atomic clock output signal within a certain range.

The traditional atomic clock steering methods can be classified into two categories including phase adjustment and frequency adjustment.

The phase adjustment method is achieved by monitoring the time difference between the atomic clock and the reference in real time. When the time difference reaches the threshold value, we should adjust atomic clock so that phase can jump directly to zero. Then the atomic clock runs freely until the threshold is reached again, and the phase is still adjusted. The phase adjustment can change phase quickly but it can't change the frequency characteristics of the signal itself. The phase adjustment method will cause phase jump, destroy the frequency stability of the signal and affect the normal use of the signal.

The frequency adjustment method is based on fully understanding the performance of the atomic clock, using a fix-predetermined frequency offset or dynamic frequency offset to adjust the atomic clock. The method allows the atomic clock to run freely to the threshold, then we should adjust the frequency offset, and make it run in the opposite direction with the new clock speed until the other threshold is reached. In that time, adjustment must be cancelled.

At present, the most used steering method is combine the phase adjustment with frequency adjustment together. The method can keep phase jump continuously, and change tendency of frequency offset quickly and improve the performance of atomic clock.

3. Dynamic Steering Method Based on Residual Correction

The steering methods mentioned before are not run automatically and intelligently. Therefore, the steering method is proposed with running automatically and intelligently which is called dynamic steering method based on residual correction.

The key idea of steering method is to predict the time difference of the next state based on the change law of historical time difference data and determine the control parameters by the forecast value, such as control period, attenuation factor and others. Therefore, the steering method is closely related to the time difference forecast. The method contains two aspects which are residual error correction method and dynamic steering method.

3.1. Residual Error Correction Method

There are many factors that affect the accuracy of time difference prediction include frequency stability, frequency drift characteristics, time difference forecast duration and time difference data quality. Time difference forecasting methods commonly used include polynomial method, grey model estimation method, neural network, etc. Due to the error of alignment link and the data processing method, it is impossible to completely match any fitted model with the true value, and there is always a deviation called the residual error between the predicted value and the true value. The residual error is usually represented with $\hat{\varepsilon}$, and the residual error visually reflects whether the fitting model is suitable.

The residual error can't be zero because of the existence of random error. The aim of model fitting is reducing the residual value constantly. The average of the residuals represents the overall offset of the data during the current control period, and reflects the predict precise of time difference fitting model. If the time difference model was corrected with the mean value of the residual, the predict value can be made closer to the true value.

Residual error correction method is a new method that converts residual to frequency deviation, and corrects it into the time difference model, and establishes a new model for the time difference forecast to reduces the residual continuously. Therefore, the residual value can change in a convergence trend and the accuracy of the forecast can improve. The flow chart of residual error correction method is as shown in Fig. 1.

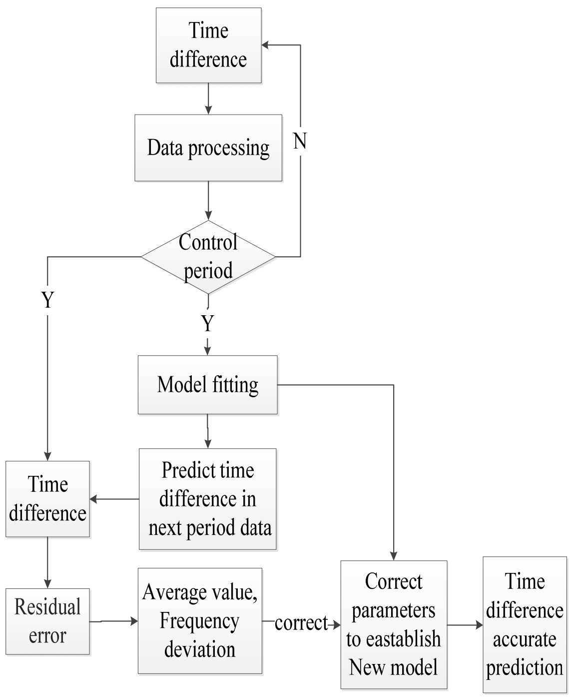

Fig. 1. The flow chart of residual error correction method.

Firstly, the time difference should be collected in real time. Until in the control period, the fitting method like least squares method should be used to establish the time difference model and calculate parameters such as phase, frequency deviation and frequency drift. Secondly, the predicted time difference in the next control period will be calculated by time difference model. Thirdly, when the true time difference of next control period is collected, the residual value can be obtained by the true value minus the predicted value. At last, it can calculate the average of the residual values of the control period in order to convert to the frequency deviation. The formula is as follows:

$$a_{\hat{\varepsilon}_1} = \frac{\sum_{j=1}^{t} \hat{\varepsilon}_j}{t} \tag{1}$$

In the formula, t represents the control period. By fitting the true value in the current control period to obtain $a_1(i+1)$. Then $a_1(i)$ is corrected with to make a new parameter $a_1'(i+1)$ and update a new time difference model. The formula is:

$$a'_{1_{i+1}} = a_{1_i} - a_{\hat{\varepsilon}_i}, i = 1,2...n \tag{2}$$

where i is the number of control period, $a_1(i+1)$ and $a_1'(i+1)$ are the first-order coefficient and the modified first-order coefficient of time difference model in i+1th control period respectively, $a_1(i)$ is the first-order coefficient of time difference model in i^{th} control period.

3.2. Dynamic Steering Method

The key idea of dynamic steering method of the atomic clock is change adjustment and control strategy to synchronize with the reference, which is according to the time difference between the atomic clock and the reference.

From the atomic clock difference model, it is obvious that the phase deviation and frequency deviation of the signal occur with timing. Based on test requirements and time difference data, adjustments and control strategies can be determined.

To determine the frequency adjustment, it is necessary to combine the time difference of the current time and the frequency deviation, which are mainly divided into four cases. It is as shown in Fig. 2.

In the first situation, it indicates that the atomic clock signal is deviating from the reference signal and the deviation speed is increased. In the second situation, the atomic clock signal is reversely deviated from the reference signal, and the deviation speed is increased.

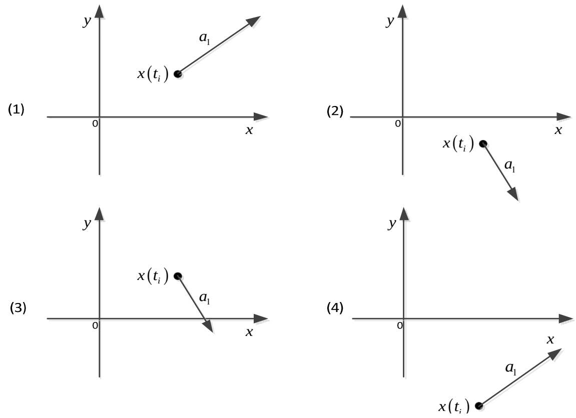

Fig. 2. Distribution of time difference and frequency deviation.

In the third case, it indicates that the atomic clock signal is approaching the reference signal from the positive direction, and the approach speed is increased. In the fourth case, it indicates that the atomic clock signal is close to the reference signal from the negative direction, and the approach speed increases.

If the first or second situation occurs, the frequency adjustment should be added to the current frequency deviation. If the third or fourth situation occurs, the frequency adjustment should be subtracted from the current frequency deviation, or the frequency adjustment should not be changed to waiting for infinite proximity.

According to the status of reference source, there are two strategies for steering which are adjustment in real time and autonomous maintenance.

When the reference source is normal, the time difference is collected and predicted in real time. according to historical data, and the trend of time difference is judged. The steering method adopts minimum control adjustment strategy, combined with the atomic clock performance, to adjust the controlled atomic clock slowly. The method maintains the accuracy and frequency stability of the output signal from controlled atomic clock. The flow chart is shown in Fig. 3.

When the time difference is great than threshold, phase adjustment is used firstly to make the phase near zero. Otherwise, time difference model is fitted by correcting the residual error. According to modified time difference model, the predicted time difference is calculated which comparing to another threshold. When the predicted time difference is great than threshold, the key parameters must be changed to adjust the clock.otherwise, the key parameters should keep for this time.

When the reference source is abnormal, previous time difference must be used. The flow chart is as shown in Fig. 4.

The time difference is predicted in real time according to historical data, and the trend of time difference is judged. When the time difference diverges, the adjustment is step by step to send to the controlled clock.

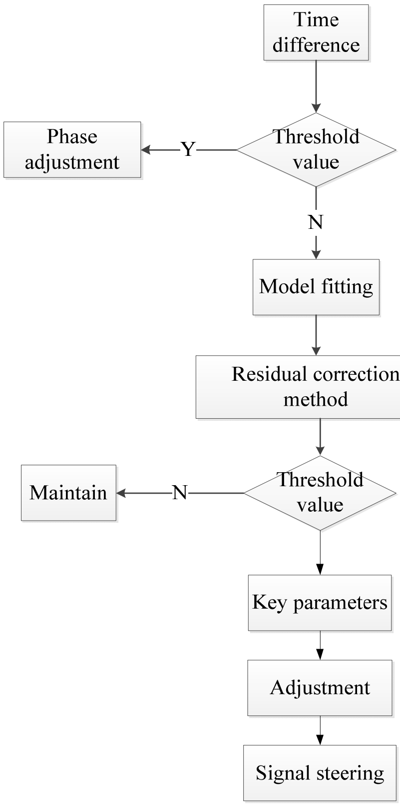

Fig. 3. Distribution of time difference and frequency deviation.

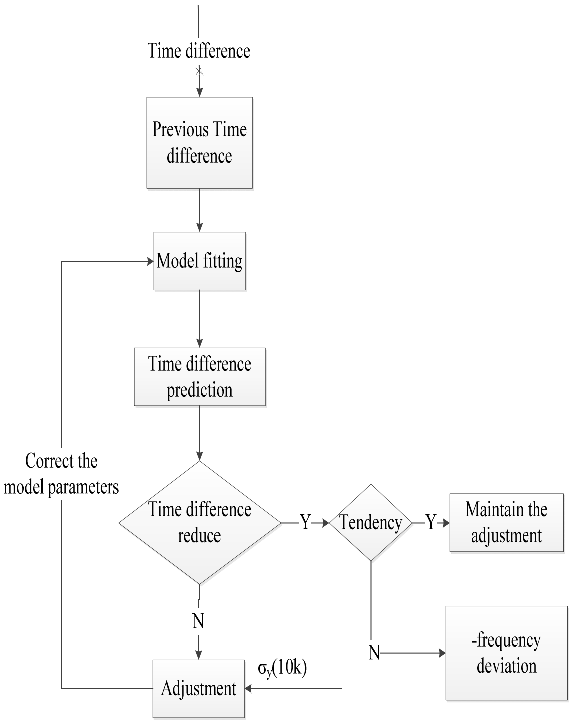

Fig. 4. Distribution of time difference and frequency deviation at abnormal reference source.

When the time difference converges, the adjustment for signal is calculated in real time based on the change trend. Until the tendency of predicted time difference reduces, the adjustment should be maintained. Otherwise, the opposite of frequency deviation must be sent to atomic clock.

4. Experimental Results

In order to further verify the dynamic control method of atomic clock based on residual correction, a test platform is designed and built. The hardware of the test platform is composed of atomic clock, high resolution offset generator(HROG-10), time interval counter(SR620), multi-channel phase measuring system(TSC MMS) and computer; the software is composed of atomic clock control software running on the industrial computer. The test platform structure is as shown in Fig. 5.

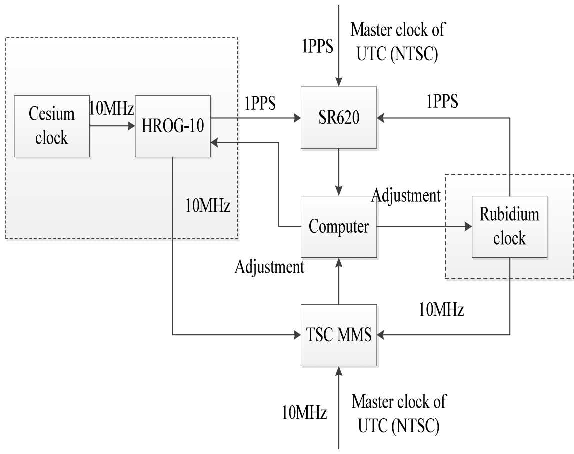

Fig. 5. The structure diagram of test platform for Cesium and Rubidium clock steering method.

Firstly, the output signal of atomic clock is divided in two signals which are 1PPS and 10 MHz signal through HROG-10. They are connected to SR620 and TSC MMS respectively. SR620 is responsible for measuring the time difference between two 1PPS signals outputted from HROG-10 and master clock of UTC (NTSC). TSC MMS is responsible for measuring the phase difference between two 10 MHz signals outputted from HROG-10 and master clock of UTC (NTSC). Secondly, the atomic clock control software designed collects the time difference and phase difference every second. According to the type of the controlled atomic clock, the key parameters and the control strategy are determined. Thirdly, the obtained adjustment is sent to HROG-10 or the atomic clock through the RS232 serial port. Therefore, it can make sure the time difference of the controlled clock signal within a certain range. At the same time, according to the phase difference of the two signals measured by TSC MMS, the frequency stability of the controlled atomic clock is calculated to determine whether the steering method affects the frequency stability of the controlled atomic clock output signal or not.

After the measurement platform is built, the master clock of UTC(NTSC) is used as the reference signal, and the output signals of Cesium clock and Rubidium are used as controlled clock respectively. The measurement results are shown in Figs. 6-11 and Table 1 that including the results of time difference and frequency stability.

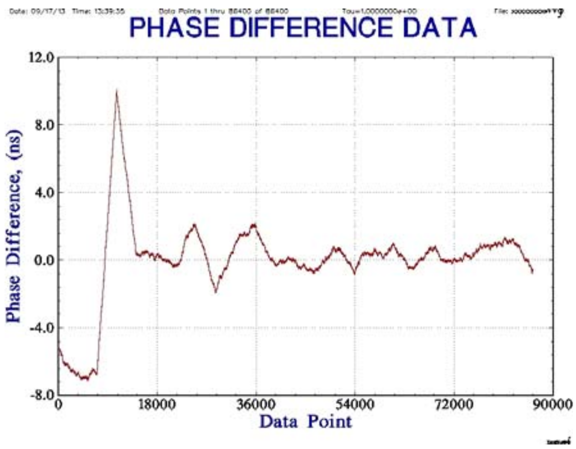

Fig. 6. The time difference data of Cesium clock steering for one day.

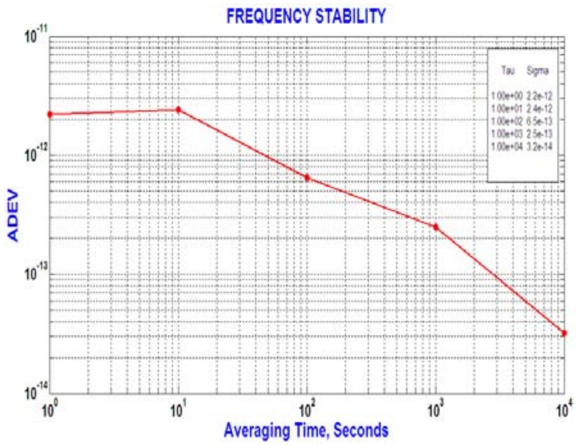

Fig. 7. Frequency stability with Cesium clock steering.

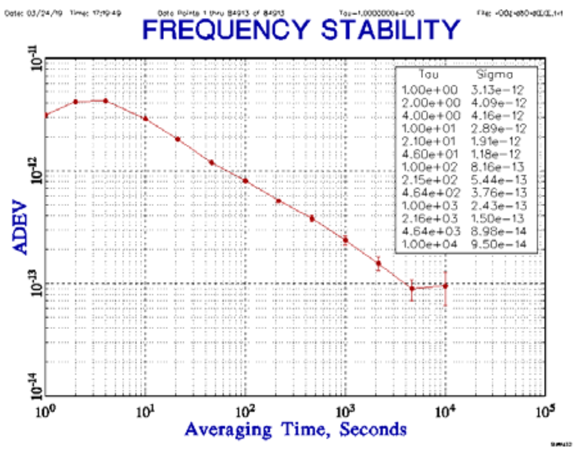

Fig. 8. Frequency stability without Cesium clock steering.

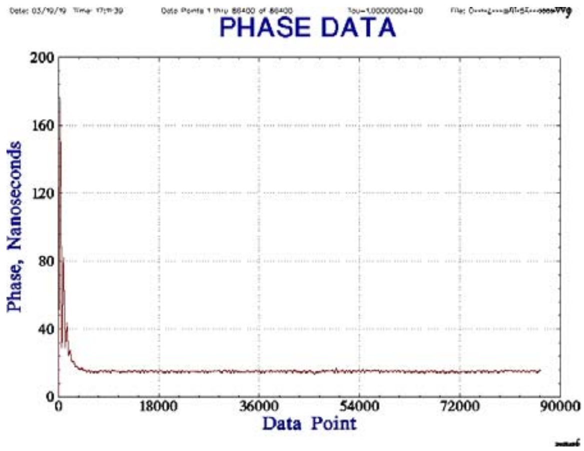

Fig. 9. The time difference data of Rubidium clock steering for one day

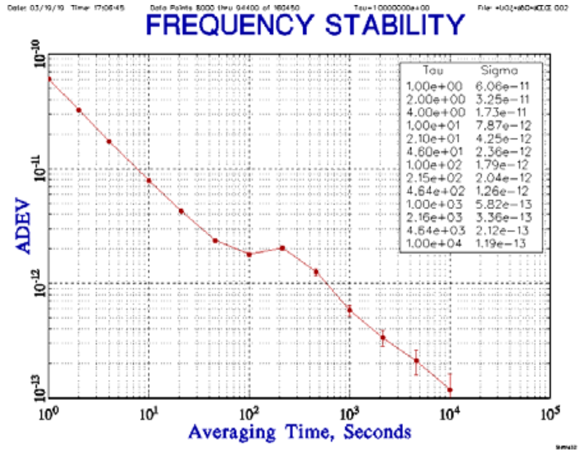

Fig. 10. Frequency stability with Rubidium clock steering.

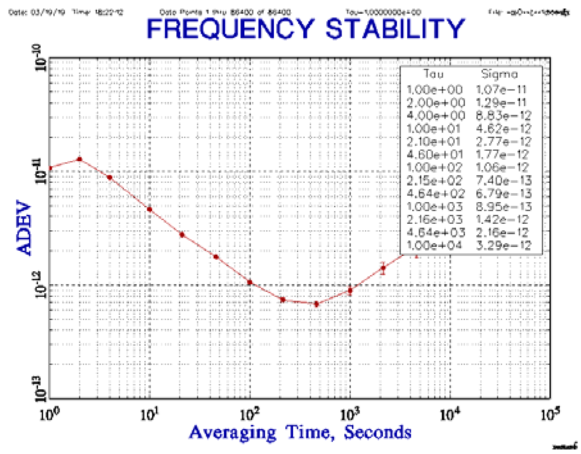

Fig. 11. Frequency stability without Rubidium clock steering.

It can be seen from Figs. 6-11 that the time difference of the running freely of Cesium clock for 16 hours is 9.4 ns. After using the dynamic steering method based on residual correction, the time difference of one day is within 2 ns. When the Rubidium clock is running freely, the time difference of one day changes quickly about 11 μs. After using the same steering method, the time difference of one day is less than 4 ns. The results show that the atomic clock dynamic steering method based on residual correction is feasible for atomic clock frequency control, especially for atomic clocks with lower frequency accuracy.

Table 1. Frequency stability of Rubidium clock and Cesium clock under two status.

Tau(s)	1	10	100	1000	10000
Cesium clock without steering	3.13 E-12	2.89 E-12	8.16 E-13	2.43 E-13	9.50 E-14
Cesium clock with steering	2.20 E-12	2.40 E-12	6.50 E-13	2.50 E-13	3.20 E-14
Rubidium clock without steering	1.07 E-11	4.62 E-12	1.06 E-12	8.95 E-13	3.29 E-12
Rubidium clock with steering	6.06 E-11	7.87 E-12	1.79 E-12	5.82 E-13	1.19 E-13

It also can be seen from Table 1 that the short-term frequency stability of the output signal of controlled Cesium clock is almost the same as which of the uncontrolled clock. Moreover, the long-term frequency stability of controlled Cesium clock is improved than which of uncontrolled clock. The short-term frequency stability of the controlled Rubidium clock is slightly lower than which of the uncontrolled clock, and the long-term frequency stability is significantly improved. The accuracy of the signal and long-term frequency stability is greatly improved with the proposed method.

The results show that the frequency stability is closely related to the measurement period and the control strategy. The measurement period of the Rubidium clock is much smaller than the period of Cesium clock. It is a very effective way to improve the long-term frequency stability of the signal by steering the atomic clock in real time.

5. Conclusion

In summary, the dynamic steering method proposed is useful for atomic clock. It makes full use of residual error to improve the accuracy of time difference prediction. The result of synchronization is at least twice as much as that of traditional methods.

The method can improve the accuracy and stability of the output signal for the atomic clock, and effectively improves the long-term stability of the signal, and shows an outstanding performance on atomic clocks with low frequency accuracy.

Acknowledgements

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