A link noise clean-up system based on fiber optical time transfer

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***Abstract*—In recent years, the fiber optic time transfer technology has experienced significant advancements in long-distance and high-precision applications, thereby playing a crucial role in both fundamental scientific research and socio-economic development. However, the 1PPS time signal is susceptible to environmental temperature fluctuations, electromagnetic interference, random vibration, and other external factors when transmitted over long distances through optical fibers. Consequently, this leads to a more pronounced deterioration of both the phase noise and stability index of the 1PPS time signal. Here, the proposed scheme introduces A link noise clean-up system based on fiber optical time transfer, utilizing low-noise narrowband digital phase-locked loops at relay sites to filter 1PPS time signals. By achieving a loop bandwidth of 1 Hz or smaller, the low-noise narrowband digital phase-locked loop effectively suppresses out-of-band noise, thereby extending the distance of time transmission and ensuring short-term stability. The experimental results demonstrate after 700km fiber optic time transmission that the TDEV of the 1PPS time signal is measured at 7.2 ps/1s, 5.51 ps/10s, and 4.91 ps/1000s. These results validate the system's performance and reliability.**

Keywords*—*time transfer, link noise, clean-up

I. Introduction

The continuous advancements in cutting-edge science and technology, such as fundamental physics research, satellite navigation and positioning, and other application domains, impose stringent requirements on the phase noise jitter and short-term stability of frequency reference sources[1-2]. Taking the time-frequency reference system of the navigation satellite system as an example, both poor short-term stability and phase noise performance deteriorate the ranging accuracy of the navigation system and the bit error rate of the navigation signal[3]. The current primary focus of major time-frequency research organizations worldwide is on frequency clean-up technology, which requires the reference frequency source to possess both long-term stability and exceptional short-term stability in order to minimize system phase jitter[4]. Currently, research on frequency cleaning technology for atomic clocks is still in its early stages, with several existing frequency clean-up devices or systems available. These include the Clean-up Oscillator manufactured by Timetech (Germany), the VCH-317 produced by VREMYA-CH (Russia), the 4145C produced by Microsemi (USA), and the A6-ANF produced by Quartzlook (UK)[5-7]. The four frequency clean-up devices have been optimized to enhance the short-term stability performance of the atomic clock's output frequency. With an Allan deviation reaching 10^{-13} orders of magnitude at , they effectively purify the input frequency source[8-10].

Although there has been some research conducted on the frequency clean-up system, there is a scarcity of relevant literature regarding the 1PPS time signal clean-up scheme, and an absence of analysis concerning short-term noise suppression in fiber optic time transfer signals as well as the development of associated equipment. Therefore, it is of great significance to carry out the fiber optic time transfer link noise purification technology for the index and implementation of long distance fiber optic time transfer system.

II. Methods

The principle of the fiber optic time transfer link noise clean-up system is shown in Fig. 1. The input 10MHz frequency reference signal is phase-identified by the PCO, and the DAC is controlled to lock onto the OCXO. The local time signal is then generated using the low-noise 10MHz output from the OCXO. The function of the TIC is to realize the measurement of the time difference between the local time signal and the reference time signal. The measurement results are processed by the operation processing unit, which eliminates noise effects and calculates the control amount required by the DAC. The operation processing unit adjusts the time-delay controller based on the calculated control quantity in order to achieve synchronization between the 1PPS time signal output from the time-delay controller and the reference time signal, thereby purifying the fiber optic 1PPS time signal and eliminating noise introduced during transmission.

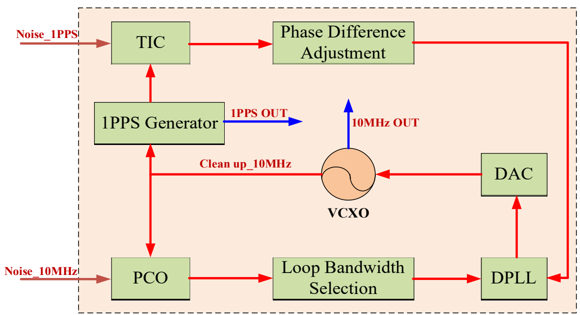

Fig.1 The link noise clean-up system based on fiber optical time transfer

PCO is the link between the fiber optic transmission frequency signal and the VCXO in the fiber optic time transmission link noise clean-up system. A PCO with low phase measurement accuracy will introduce excessive noise into the system, resulting in a decline in frequency purification performance. This paper adopts the double mixing time difference measurement scheme, which utilizes the intermediary source and the reference and measured simultaneous mixing generates a differential beat frequency signal, measures the phase difference of the differential beat signal, and then calculates the phase difference of the input signal.

The reference signal and the signal to be measured are respectively mixed with the intermediary source, and then converted into a digital signal by a low-pass filter and a zero-crossing detector (ZCD). Finally, the time difference is measured by a time interval counter, yielding the time difference and phase difference of the oscillator to be measured. Therefore, the reference signal frequency, the signal frequency to be measured, and the time errors of both mixers are:

$$x_{ref-mid}(t)=\frac{\varphi_{ref}(t)-\varphi_{mid}(t)}{2\pi\left(f_{ref}-f_{mid}\right)} \tag{1}$$

$$x_{tex-mid}(t)=\frac{\varphi_{tex}(t)-\varphi_{mid}(t)+\varphi_s}{2\pi\left(f_{tex}-f_{mid}\right)} \tag{2}$$

The V_{ref} , V_{mid} , and V_{tex} represents the amplitude of the signal, V_{mid} 、 V_{tex} represents the frequency of the reference signal, f_{mid} represents the frequency of the intermediary source, f_{tex} represents the signal to be measured, and $\varphi_{ref}(t)$, $\varphi_{mid}(t)$, and $\varphi_{tex}(t)$ represent their respective initial phases.

According to equations (1) and (2) it can be deduced that the value of the clock difference between the frequency of the reference signal and the frequency of the signal to be measured, and between the two mixers is:

$$x_{ref-tex}(t)=\frac{\varphi_{ref}(t)f_{tex}-\varphi_{tex}(t)f_{ref}}{2\pi f_{ref}f_{tex}} \tag{3}$$

$$\begin{aligned} x_{(ref-mid)-(ref-mid)}(t) &= \frac{\varphi_{ref}(t)\left(f_{tex}-f_{mid}\right)}{2\pi\left(f_{ref}-f_{mid}\right)\left(f_{tex}-f_{mid}\right)} \\ &+\frac{\varphi_{mid}(t)\left(f_{ref}-f_{tex}\right)}{2\pi\left(f_{ref}-f_{mid}\right)\left(f_{tex}-f_{mid}\right)} \\ &-\frac{\left(\varphi_{tex}(t)+\varphi_s\right)\left(f_{ref}-f_{mid}\right)}{2\pi\left(f_{ref}-f_{mid}\right)\left(f_{tex}-f_{mid}\right)} \end{aligned} \tag{4}$$

The above equation indicates that, ideally, the measurement resolution of $x_{(ref-mid)-(ref-mid)}$ is $\frac{f_{ref}}{f_{ref}-f_{mid}}$ times greater than that of $x_{ref-tex}(t)$. The measurement resolution of 10^5 can be enhanced by utilizing the double-mixing time difference method for time difference measurement, given a reference signal frequency of 10 MHz and a differential frequency rate $f_{ref}-f_{mid}$ of 100 Hz between the reference signal frequency and the intermediary source frequency.

The TIC is an essential component in achieving a low-noise narrow-band phase-locked loop, and its accuracy determines the precision of the phase-locked loop. The method used in this paper belongs to the time broadening method for simulating interpolation-capacitor charging and discharging. The time interval between the signals of opening and closing the door is converted into a positive pulse width T. This pulse width T is then filled with 80 MHz time base pulses to obtain an integer count value that represents the measured time interval. The phase difference between the time base pulse signal and the opening and closing of the door, which represents the measurement of the zero part of the time interval, is a distinctive characteristic of this scheme. The proposed method utilizes a voltage source instead of a high-speed current source, deviating from the conventional approach to time-amplitude conversion. This substitution not only enhances stability but also guarantees superior measurement resolution. A narrow pulse (<12.5ns) is formed by the phase difference between the time base pulse signal and the opening and closing of the door, which charges the capacitor. The amount of charge on the capacitor is directly related to the width of this high-resolution narrow pulse.

In this paper, the low noise narrowband filters is a second-order loop filter with an operational amplifier. The transfer function of a second-order loop can generally be represented by two loop parameters, namely the intrinsic frequency ω_n and the damping coefficient ξ . These parameters effectively capture the characteristics of the loop to some extent. Their expressions are:

$$\omega_n=\sqrt{\frac{K_0\left(K_d^f+K_d^t\right)}{\tau_1}}=\sqrt{K_0\left(K_d^f+K_d^t\right)K_2} \tag{5}$$

$$\xi=\frac{\tau_2}{2}\sqrt{\frac{K_0\left(K_d^f+K_d^t\right)}{\tau_1}}=\frac{K_1}{2}\sqrt{\frac{K_0\left(K_d^f+K_d^t\right)}{K_2}} \tag{6}$$

The value of ξ is typically chosen within the range of 0.5 to 2, with 0.707 being the most commonly utilized value. Loops with damping less than 0.5 exhibit excessive overshoot in their transient response, which renders their dynamic performance unsatisfactory. The use of damping factors greater than 1 is limited to specific exceptional cases. Furthermore, the value range of ω_n spans from 10-5 to 108 rad/s.

In fact, the low-noise narrow-band phase-locked loop is primarily influenced by the phase noise of both the input frequency source and the OCXO. For the selection of the optimal bandwidth can follow the neighborhood of the cross frequency of the input frequency and the phase noise spectrum of the OCXO noise source.

III. RESULTS

The test program is designed to fully verify the noise purification effect of the fiber optic time transmission link. A test environment is established, and the standard time UTC (NTSC) master clock 1PPS signal with 10MHz synchronization is used as the signal source for simulating load-induced noise tests. After loading noise test purification performance through signal source simulation, the 1PPS signal of the standard time UTC (NTSC) main clock and 10MHz signal are tamed to the OCXO after passing to the remote end through optical fiber, and the performance indexes of the 1PPS time signal before and after the taming are compared and analyzed.

For the performance test method of the noise purification system for fiber optic time transmission link, two homogeneous 1PPS signals and two homogeneous 10MHz signals are output from the signal source. One channel of 1PPS signal is used as the opening signal, and one channel of 10MHz signal is used as the clock reference input to SR620. Another 1PPS signal and 10MHz signal are loaded with 1%, 2%, 3%, 10%, and 20% noise input to the clean-up system. The clean-up system outputs 1PPS to SR620 as a closing signal to test the performance indicators.

As shown in Fig. 2, after loading 1% noise, the peak-to-peak value is 162 ps, and the corresponding TEDV deteriorates to 25.6 ps/1s and 7.68 ps/10s. After the noise signal passed through the clean-up system, the fast noise of the 1PPS time signal was suppressed, and the peak-to-peak value was reduced to 41ps, with TDEVs of 5.34ps/1s and 1.87ps/10s. The peak-to-peak value of 1PPS reached 1949ps with TDEVs of 252ps/1s and 78ps/10s when the noise was amplified to 10%. After passing through the clean-up system, the peak-to-peak value of 1PPS decreased to 48ps with TDEVs of 5.96ps/1s and 2.09ps/10s. The observed phenomenon is that when the noise signal is loaded to 20%, the peak-to-peak value reaches 3630 ps, with a TDEV of 507 ps/1s and 174 ps/10s. The performance of low-noise narrow-band phase-locked loops is primarily influenced by the phase noise originating from the input frequency source and the OCXO, while narrow-band phase-locked filters exhibit loop bandwidths as low as 1 Hz or even lower. The noise signal inputted to the purification system causes the low-noise narrow-band phase-locked loop to become unlocked, resulting in a lack of purification. Although phase-locked loops have good immunity to interference, in high noise environments, the phase comparator may misjudge and cause the phase-locked loop to unlock due to noise interference. Since the phase jitter of 1PPS for long-distance fiber time transfer does not exceed the ns order of magnitude. Therefore, the fiber optic time transfer link noise purification scheme proposed in this paper can accomplish the 1PPS purification effect within the operating bandwidth.

The phase noise of a 10 MHz frequency signal after passing through the purification system is shown in Fig. 3:

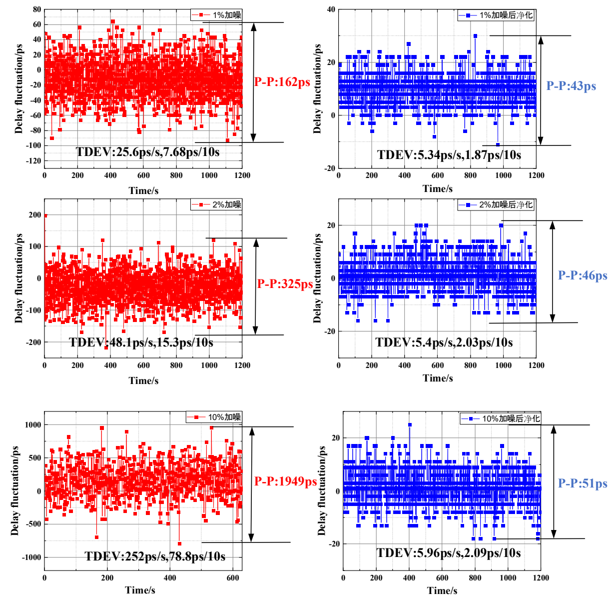

Fig.2 Signal source simulation noise test

The phase noise of the clean-up 10 MHz carrier signal is as follows: -109.2dBc/Hz@0.1Hz, -129.5dBc/Hz@1Hz, -147.7dBc/Hz@10Hz, -154.2dBc/Hz@100Hz, -156.5dBc/Hz@1KHz, -155.7dBc/Hz@10KHz, -157.2dBc/Hz@100KHz, and -156.6dBc/Hz@1MHz

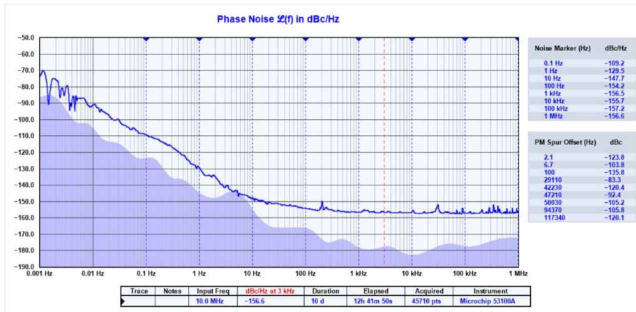

Fig.3 10MHz phase noise after link noise clean-up

After conducting purification performance testing by simulating the loading noise from the signal source, the 1PPS signal of the standard time UTC (NTSC) master clock and the 10MHz signal are transmitted to the remote end of 700km through fiber optic cables for OCXO taming. The performance indicators of the 1PPS time signal before and after taming are compared and analyzed.

As shown in Fig.4, after the 1PPS signal from the reference source and the 10MHz signal passed through the 700km fiber optic link, the measured time deviation SD of the 1PPS was found to be 30.02ps with a peak-to-peak value of 326ps, and corresponding TDEVs were calculated as follows: 18.38ps/1s, 8.96ps/10s, and 4.87ps/1000s. After undergoing purification system under the same fiber link conditions, the standard deviation (SD) of 1PPS time deviation was measured to be 17.9 ps with a peak-to-peak value of 128 ps. The corresponding TDEVs were determined as 7.2 ps/1s, 5.51 ps/10s, and 4.91 ps/1000s. Upon comparing the two data sets, it is evident that the fiber optic time transfer link noise purification system exhibits superior suppression capabilities for fast jitter noise in signals and enhances the short-term stability index of 1PPS. However, when considering long-term stability indicators such as kilosecond stability, the effectiveness of fiber optic time transmission link noise purification remains unchanged or slightly decreased. This is because the low-noise narrow-band phase-locked loop of the link noise purification system has a filtering effect on the fast 1PPS delay jitter. However, it also superimposes device cascade noise, which is a chronic long-term drift caused by temperature and aging, ultimately affecting the long-term stability of fiber optic time delivery.

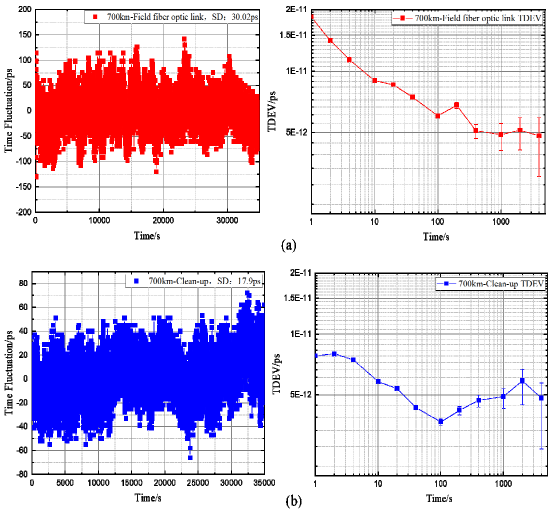

Fig.4 700km field optical fiber time transmission 1PPS time deviation and TDEV

IV. Conclusions

The suppression ability of fast noise is significantly reduced with the growth of transmission distance and the increase in transmission delay, leading to ineffective real-time control of fast delay jitter. Therefore, the fiber optic link noise becomes the primary factor affecting short-term stability of fiber optic timing. This paper proposes a link noise clean-up scheme in fiber optic time transmission. The 10MHz carrier signal is recovered from the receiver at the relay station and cleaned up by a low-noise narrow-band phase-locked filter. The clean-up 10MHz carrier signal is divided into 1PPS time signals in order to reduce the random jitter introduced by the superior fiber optic transmission of 1PPS. The final test was validated in a laboratory signal source simulating noise as well as in a field fiber delivery environment.

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