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Research on Airborne Time and Frequency Synchronization Technologies for Aircraft

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Abstract

This paper systematically investigates airborne time and frequency synchronization technologies, overall system architectures and major technical challenges under complex and harsh aerospace environments. It analyzes feasible synchronization methods including satellite timing and two-way time comparison, presents two typical system architectures, elaborates on core critical technologies, discusses future development trends, and verifies the synchronization precision and operational reliability of relevant equipment, providing solid technical support for stable operation of avionic systems and efficient implementation of cooperative combat missions.

Keywords

Airborne time and frequency synchronization, Avionic systems, High-precision time synchronization, Satellite-based time synchronization, IRIG-B code,Low phase-noise crystal oscillator, Rubidium atomic clock, Radar networking, Passive localization, Anti-vibration.

1. Introduction

In the domain of modern aerial warfare, the operational paradigm has gradually evolved from traditional single-platform combat to multi-platform cooperative operations and even system-level combat represented by network-centric warfare. With the rapid development and wide application of advanced combat technologies such as stealth technology, electronic countermeasures, and precision guidance, time and frequency synchronization has become an indispensable and fundamental supporting technology in a variety of critical airborne applications, including airborne information fusion, radar networking, passive localization, and other tactical cooperative applications, as well as large-scale system-of-systems combat represented by network-centric warfare. In modern combat scenarios, the operational efficiency, target detection capability, positioning accuracy, and information fusion performance of combat aircraft are highly dependent on the consistency and accuracy of time and frequency among different airborne sensors, communication systems, weapon systems, and electronic devices. Therefore, the research, design, and engineering implementation of high-performance airborne time and frequency synchronization systems have become core technical links that must be broken through in the development of next-generation avionic systems[1-5].

The airborne environment is extremely harsh compared with ground environments, which puts forward strict requirements on the performance of time and frequency synchronization systems. During the flight of the aircraft, it will face high-speed dynamic movement (speed up to Mach 2 or higher), large temperature changes (ranging from -45℃ to 70℃), strong random vibration (acceleration up to 10g or more), complex electromagnetic interference (including intentional jamming and unintentional interference from airborne electronic equipment), as well as constraints such as limited installation space and power consumption. These harsh conditions will seriously affect the stability and accuracy of the time and frequency synchronization system, making the research and development of airborne time and frequency synchronization technologies more challenging than ground-based systems. For instance, high-speed dynamic movement will cause Doppler shift of synchronization signals, while large temperature fluctuations will lead to frequency drift of clock sources, and strong vibration will degrade the phase noise performance of oscillators, all of which jointly affect the synchronization precision[6-8].

In general, the time synchronization accuracy required by airborne information fusion systems ranges from the microsecond (μs) level to the millisecond (ms) level. For example, the time synchronization accuracy required for airborne multi-sensor data fusion in medium-range air combat scenarios is about 1μs to 10μs, which can ensure the consistency of target position and state information collected by different sensors. For specific radar networking applications, especially airborne radar networking systems, the demand for time synchronization accuracy is more stringent. Airborne radar networking is to form a distributed radar system by networking the radars of multiple aircraft platforms, which can achieve long-range, high-precision detection and tracking of targets. To achieve the expected ranging accuracy and spatial resolution, the time synchronization accuracy between different radar nodes must be controlled within a fraction of the compressed pulse width. For example, if the compressed pulse width of the radar is 10ns, the time synchronization error between radar nodes must be less than 2ns, otherwise the ranging error and angle measurement error of the radar network will increase sharply. If the time synchronization error exceeds the allowable range, the ranging error and angle measurement error of the radar network will increase sharply, which will seriously affect the overall detection performance of the entire radar system, and even lead to the failure of the radar network to effectively detect and track targets. For example, in a typical airborne radar networking system with a baseline distance of 50km, a time synchronization error of 5ns will lead to a ranging error of about 1.5 meters, which is unacceptable for precision strike missions[9-13].

Based on the above analysis, it can be seen that time and frequency synchronization is no longer an auxiliary technology in the avionic system, but has become a necessary prerequisite and core basic support for the normal operation of various key systems of combat aircraft. The performance of the airborne time and frequency synchronization system directly determines the overall combat effectiveness, situational awareness ability, information transmission efficiency, and weapon delivery accuracy of the aircraft. Therefore, in-depth research on airborne time and frequency synchronization technologies, system architectures, key devices, and engineering implementation methods is of great theoretical significance and important military application value for improving the combat capability of China's military aircraft, breaking through foreign technical blockades, and realizing the independent and controllable development of avionic systems[14-16].

2. Airborne Time and Frequency Synchronization Technologies

2.1. Transported Clock Technology

Transported clock synchronization is a traditional high-precision time synchronization method, which realizes time and frequency transmission and synchronization by physically moving a high-precision atomic clock or crystal oscillator between different nodes. This technology has a long history of application and is widely used in ground-based high-precision time synchronization scenarios. In practical applications, a high-stability, high-accuracy master clock (usually a cesium atomic clock or a rubidium atomic clock) is placed at the reference node, and then the same high-performance clock is moved to the slave node for comparison and calibration. After calibration, the slave node can maintain high-precision time and frequency output for a certain period, and the maintenance time is determined by the stability of the clock itself. For example, a rubidium atomic clock can maintain high-precision synchronization for several days to several weeks after calibration, while a cesium atomic clock can maintain it for several months[17-20].

In engineering applications, the time synchronization accuracy that can be achieved by transported clock technology is about 0.1 microseconds (μs), and the frequency calibration accuracy can reach the order of magnitude of 10^{-13}. This technology has the advantages of high precision, no dependence on wireless signals or communication networks, and strong confidentiality. Since it does not need to transmit time and frequency signals through external channels, it is not affected by electromagnetic interference, which is very suitable for scenarios with high confidentiality requirements[21-22].

2.2. Short-Wave Time Synchronization Technology

Short-wave time synchronization uses short-wave radio signals (frequency range 3MHz to 30MHz) to transmit time and frequency information. Short-wave signals can be transmitted over long distances through ionospheric reflection, so they can cover a wide area, and the equipment is simple and low-cost, which is widely used in civilian and general military low-precision time synchronization scenarios. The working principle of short-wave time synchronization is that the time service station transmits standard time and frequency signals through short-wave transmitters, and the receiver receives the signals, demodulates the time information, and calibrates the local clock. The short-wave time service system is relatively simple in structure, and the receiver can be miniaturized, which has a certain application value in low-cost and low-precision scenarios.

2.3. Long-Wave Time Synchronization Technology

Long-wave time synchronization mainly uses long-wave ground-wave and sky-wave signals (frequency range 30kHz to 300kHz) to transmit standard time and frequency signals. Compared with short-wave signals, long-wave signals have strong diffraction ability, stable propagation, and relatively small attenuation, so they can achieve higher synchronization accuracy than short-wave. Long-wave ground-wave signals propagate along the ground surface, with stable propagation path and small delay variation, while long-wave sky-wave signals propagate through ionospheric reflection, with a longer transmission distance but affected by ionospheric changes. Long-wave signals are less affected by weather conditions than short-wave signals, and their propagation stability is significantly better.

2.4. Satellite-Based Time and Frequency Synchronization Technology

Satellite-based time and frequency synchronization is currently the most widely used, most practical, and most important time synchronization method in the world. It uses navigation satellite systems (such as GPS, Beidou, GLONASS, Galileo, etc.) to broadcast standard time and frequency signals to the world, which can realize all-weather, full-area, high-precision time and frequency transmission for ground, sea, air, and space platforms. Compared with other time synchronization technologies, satellite-based time and frequency synchronization has the advantages of wide coverage, high precision, real-time performance, good dynamic adaptability, and simple equipment, which is very suitable for airborne platforms with high-speed movement and long-distance operation. Therefore, satellite timing has become the preferred and basic time synchronization means for airborne systems. In modern military aircraft, satellite-based time synchronization is usually the core of the airborne time and frequency synchronization system, and other synchronization technologies are used as backups.

Satellite time synchronization includes multiple working modes, which are suitable for different airborne application scenarios:

One-way satellite timing: The receiver directly receives the satellite time signal, and calculates the time difference between the local clock and the satellite time according to the signal propagation delay. The typical time synchronization accuracy is about 20 ns. This mode has the advantages of simple equipment, low power consumption, and fast synchronization speed, which is suitable for most airborne applications with medium precision requirements, such as airborne communication systems, general sensor synchronization, and other scenarios. It is the most commonly used mode in airborne satellite synchronization systems due to its simplicity and reliability.

Satellite common-view time synchronization: By observing the same satellite at the same time at two nodes (such as two aircraft platforms), the time difference between the two nodes can be eliminated by using the common satellite signal, and the synchronization accuracy can reach about 5 ns. This mode is suitable for multi-platform cooperative operations, such as airborne radar networking and multi-platform passive positioning, which require high-precision time synchronization between multiple platforms. In practical applications, multiple aircraft can achieve high-precision inter-platform synchronization through satellite common-view mode, laying a foundation for cooperative combat.

Two-way satellite time comparison based on communication satellites: Through two-way information interaction between two nodes via communication satellites, the propagation delay of signals in both directions is measured and compensated, and the synchronization accuracy can reach the hundreds of picoseconds (ps) level, and the frequency calibration accuracy can reach up to 10^{-15}, which is one of the highest precision satellite synchronization methods at present. This mode is suitable for ultra-high-precision airborne applications, such as high-precision passive positioning, space-based measurement and control, and other scenarios, but the equipment is complex and the cost is high, so it is only used in high-end military aircraft and special mission aircraft.

In airborne applications, the Beidou navigation satellite system developed independently in China has obvious advantages. The Beidou system has the functions of positioning, navigation, and time service, and can provide all-weather, high-precision time and frequency signals for airborne platforms. Compared with GPS, the Beidou system has better anti-interference performance and higher security, which is more suitable for military airborne applications. The airborne Beidou receiver can adapt to the high dynamic movement of the aircraft, with a dynamic range of up to ±6g, and can effectively compensate for the Doppler shift caused by high-speed movement, ensuring the stability and accuracy of time synchronization. In addition, the Beidou system has a regional enhancement function, which can further improve the synchronization accuracy in key areas.

However, satellite-based time and frequency synchronization also has certain limitations: it is easily affected by intentional jamming and unintentional interference. In modern electronic warfare, the enemy may use jamming equipment to interfere with satellite signals, resulting in the receiver being unable to receive valid signals, thus affecting the synchronization effect. In addition, when the aircraft flies in areas with severe shielding (such as mountainous areas, urban canyons, or under the cover of clouds and fog), the satellite signal may be blocked, resulting in temporary loss of synchronization. Therefore, the airborne time and frequency synchronization system usually combines satellite timing with other synchronization technologies to form a redundant backup system, ensuring the reliability and continuity of synchronization. For example, when satellite signals are interrupted, the system can switch to the internal rubidium atomic clock for autonomous timekeeping, maintaining high-precision synchronization for a certain period.

2.5. Optical Fiber Time and Frequency Transmission Technology

Optical fiber time and frequency transmission uses optical fiber communication networks to transmit high-precision time and frequency signals. Optical fiber has the characteristics of ultra-low loss, ultra-high bandwidth, strong anti-electromagnetic interference ability, and stable transmission performance, which is an ideal medium for high-precision long-distance time and frequency transmission. In recent years, with the rapid development of optical fiber communication technology, optical fiber time and frequency transmission technology has made great progress, and its synchronization accuracy has reached the picosecond level, which is widely used in ground-based high-precision time and frequency networks, aerospace measurement and control networks, and other scenarios. It is especially suitable for ground fixed nodes that require ultra-high precision synchronization.

At present, the time transmission accuracy using the communication optical fiber network can be better than 100 ps, and the frequency transmission accuracy can be better than 10^{-19}, which is the highest precision time and frequency transmission technology recognized in the world. Optical fiber transmission will be an important technical means for future national-level high-precision time and frequency networks, aerospace measurement and control networks, and military communication networks. However, limited by the wired transmission mode, optical fiber synchronization can only be used in fixed or wired-connected systems, and cannot be directly applied to airborne mobile platforms. Because the aircraft is in high-speed dynamic movement, it is impossible to maintain a fixed optical fiber connection with the ground or other platforms. Therefore, optical fiber time and frequency transmission technology can only be used for ground support systems of aircraft, such as ground-based time and frequency reference stations, airborne equipment ground calibration systems, etc., and is an important supplementary technology for airborne time and frequency systems.

2.6. Internet-Based Time Synchronization Technology

Internet-based time synchronization mainly uses network time protocols such as NTP (Network Time Protocol) and PTP (Precision Time Protocol) to realize time synchronization between network nodes. This technology is widely used in civilian networks, industrial control systems, and other scenarios, with the advantages of simple implementation and low cost. The working principle is that the time server provides standard time signals, and the client node communicates with the time server through the network, obtains the time difference between the local clock and the standard time, and calibrates the local clock. This technology is mature and widely used in civilian fields, but its application in airborne scenarios is limited.

2.7. IRIG-B Code Synchronization Technology

IRIG-B code is a kind of time information coding format widely used in military and industrial fields, which is formulated by the Inter-Range Instrumentation Group (IRIG). IRIG-B code has two types: AC-coupled IRIG-B (AC) code and DC-coupled IRIG-B (DC) code. Among them, IRIG-B (DC) code is a DC-coupled time code, which has strong anti-interference ability, simple decoding, and is suitable for internal time distribution of various systems, especially in harsh electromagnetic environments such as airborne. IRIG-B (DC) code is widely used in airborne avionic systems due to its good environmental adaptability.

The IRIG-B (DC) code contains rich time information, including year, month, day, hour, minute, second, and millisecond, which can be decoded by the receiver to obtain accurate time information. When IRIG-B (DC) code is used together with two-way time comparison technology, the time synchronization accuracy can reach the nanosecond (ns) level, which can fully meet the high-precision time distribution requirements inside the aircraft. The working principle is that the airborne time and frequency synchronization system generates standard IRIG-B (DC) code signals, which are transmitted to each time-using unit (such as sensors, communication equipment, weapon systems) through the internal bus of the aircraft. Each time-using unit decodes the IRIG-B (DC) code signals and calibrates its own internal clock to achieve time synchronization. The decoding process of IRIG-B (DC) code is simple, and the equipment cost is low, which is conducive to large-scale application in airborne systems.

IRIG-B (DC) code has the advantages of strong anti-interference ability, simple equipment, and easy integration, which is very suitable for the internal time distribution of airborne avionic systems. At present, IRIG-B (DC) code has become the main standard interface and time transmission code for internal time synchronization of airborne avionic systems, and is widely used in various military aircraft and civil aircraft. In addition, IRIG-B (DC) code can also be combined with satellite timing technology to form a hybrid synchronization system, which not only ensures the high precision of internal synchronization, but also realizes the synchronization between the aircraft and the external reference time source. This hybrid system combines the advantages of satellite synchronization and IRIG-B code synchronization, improving the reliability and precision of the entire system.

3. Airborne Time and Frequency Synchronization System Architecture

The airborne time and frequency synchronization system architecture is the core of the entire synchronization system, which determines the working mode, synchronization accuracy, reliability, and anti-interference ability of the system. According to different working modes and security design concepts, the current airborne time and frequency synchronization system mainly adopts two types of system architectures: non-synchronized local time architecture and direct synchronized local time architecture. These two architectures have their own advantages and disadvantages, and are suitable for different airborne application scenarios. This chapter will introduce the two architectures in detail, and analyze the composition and working principle of the airborne time and frequency synchronization system.

3.1. First Architecture: Local Time Not Synchronized with External Reference Source

In this architecture, the local time of the aircraft is not directly locked or synchronized with the external reference time source (such as satellite time). The system only measures the time difference between the local clock and the external reference time source in real time, and then distributes the measured time difference data to each time-using unit in the avionic system through the internal data link. Each time-using unit uses the local time as the reference time for data collection and processing, and corrects the data according to the received time difference data to ensure the consistency of the data between different time-using units. This architecture emphasizes the independence of the local clock, which is suitable for high-threat combat environments.

The core of this architecture is the independent operation of the local clock. The local clock is usually a high-stability crystal oscillator or rubidium atomic clock, which can maintain stable time and frequency output for a long time without relying on external reference signals. The time difference measurement unit measures the time difference between the local clock and the external reference time source in real time, and the measurement accuracy can reach the nanosecond level. The time difference information distribution unit transmits the time difference data to each time-using unit through the internal data link (such as 1553B bus, Ethernet, etc.), and each time-using unit completes the data correction according to the time difference data. The 1553B bus is widely used in airborne systems due to its high reliability and real-time performance, which can ensure the timely transmission of time difference data.

The advantage of this architecture is that the local clock works independently and is not affected by the abnormality or interruption of external signals, so the security, reliability, and anti-interference ability of the local time are extremely high, which is very suitable for high-threat battlefields with complex electromagnetic environments. For example, when the satellite signal is jammed or blocked, the local clock can still maintain stable operation, and each time-using unit can continue to work normally by using the local time and the last measured time difference data, ensuring the continuity of the system's work. In addition, this architecture has strong flexibility, and can adapt to different external reference time sources, and can switch between different reference sources according to the actual situation. It can also adapt to scenarios where external reference signals are intermittent or unstable.

However, its disadvantage is also very obvious: each time-using device on the aircraft needs to receive and process additional time difference information, which increases the design complexity, calculation load, and software and hardware overhead of the terminal equipment. For example, each sensor needs to be equipped with a dedicated time difference processing module to correct the collected data, which increases the volume and power consumption of the sensor. In addition, the accuracy of data correction depends on the real-time performance and accuracy of time difference measurement. If the time difference measurement has errors or delays, it will affect the accuracy of data correction, thereby reducing the performance of the system. This architecture is more suitable for aircraft with high requirements on anti-interference ability and can accept higher terminal equipment complexity.

3.2. Second Architecture: Local Time Directly Synchronized with External Reference Source

In this architecture, the airborne time and frequency system directly synchronizes the local time with the external reference time source, and calibrates the local high-stability clock source (such as crystal oscillator or rubidium atomic clock) in real time according to the received reference signal. The local clock is locked to the external reference time source, and its time and frequency output are consistent with the external reference time source. Each time-using unit on the aircraft directly uses the local time as the reference time, without the need to process additional time difference information. This architecture is simple in structure and high in real-time performance, which is widely used in most airborne scenarios.

The core of this architecture is the real-time calibration of the local clock. The time source selection unit selects the optimal external reference time source (such as satellite time) according to the signal quality and working mode, and the time difference measurement unit measures the time difference between the local clock and the external reference time source. The local time reference unit calibrates the local clock in real time according to the time difference data, so that the local clock is always synchronized with the external reference time source. The synchronous signal generation unit generates standard IRIG-B (DC) code signals and other synchronous pulse signals, which are distributed to each time-using unit to ensure the consistency of time among all units. The real-time calibration of the local clock ensures the high precision of the entire system.

The biggest advantage of this architecture is that there is no need to distribute time difference information to each terminal device, which greatly reduces the processing pressure and design complexity of each time-using unit, simplifies the system structure, and improves the real-time performance. For example, the sensor can directly use the local time to stamp the collected data, without the need for additional data correction, which reduces the software and hardware overhead of the sensor and improves the data processing efficiency. In addition, this architecture has high synchronization accuracy, because the local clock is calibrated in real time by the external reference time source, and the time deviation can be controlled within the nanosecond level. This architecture is suitable for most airborne applications that require high real-time performance and low terminal complexity.

However, this architecture puts forward higher requirements for the reliability, stability, and anti-interference ability of the airborne time and frequency synchronization equipment itself. Since the local clock is highly dependent on the external reference time source, if the external reference signal is abnormal or interrupted, the local clock will lose synchronization, and its time and frequency output will drift over time. Therefore, the system needs to have strong autonomous timekeeping capability. When the external signal is interrupted, the local clock can maintain high-precision time and frequency output for a certain period (usually several hours to several days) to ensure the normal operation of each time-using unit. In addition, the system needs to have strong anti-interference ability to resist the interference of external electromagnetic signals and ensure the stability of the external reference signal reception. To improve reliability, this architecture usually adopts redundant design for key components.

3.3. Composition of Airborne Time and Frequency Synchronization Architecture

Regardless of which system architecture is adopted, the airborne time and frequency synchronization system is mainly composed of six functional modules, which work together to realize high-precision time and frequency synchronization. The specific composition is shown in Figure 1 (Airborne Time-Frequency Synchronization Architecture Schematic), and each module's function is detailed as follows:

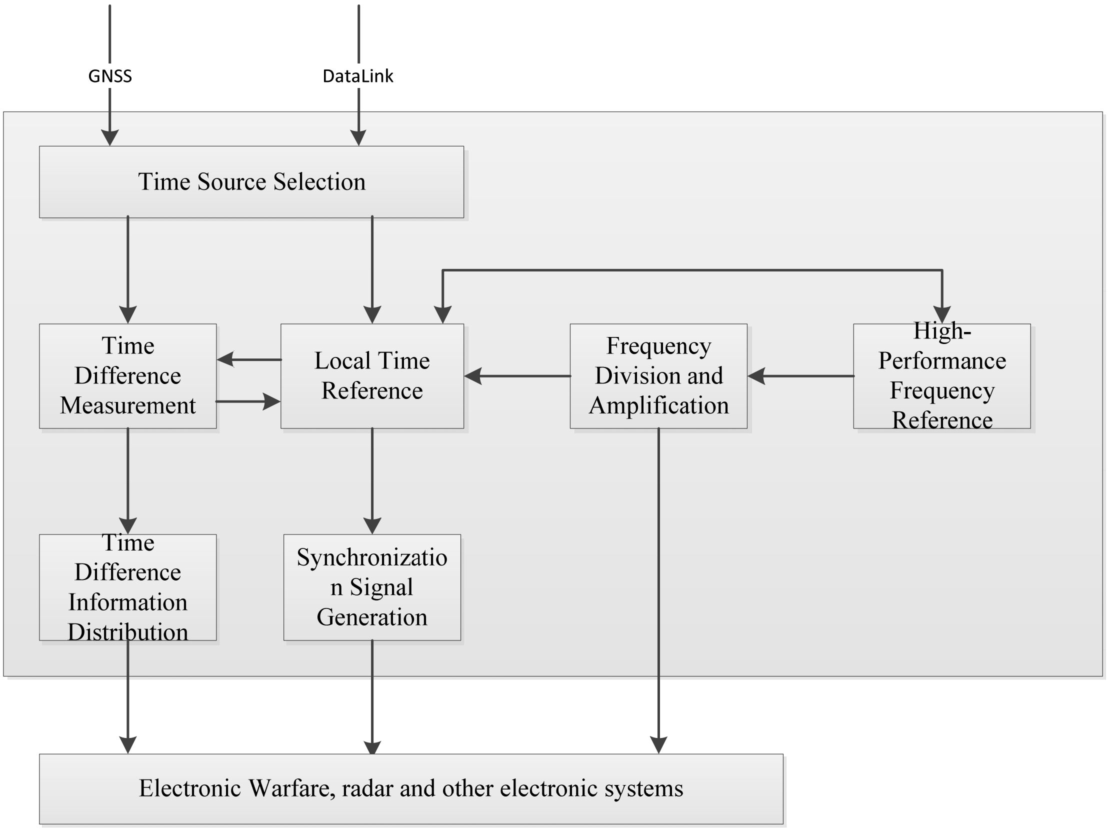

Figure 1. Airborne Time-Frequency Synchronization Architecture Schematic

The airborne time and frequency synchronization system architecture is mainly composed of the following functional modules:

Time Source Selection Unit: According to the pre-set configuration, signal quality, and working mode, the system automatically or manually selects the optimal time source (such as satellite time, two-way comparison time, internal holdover time, etc.) as the reference for local time generation.

Time Difference Measurement Unit: Realizes high-precision measurement of the time difference between local time and reference time, and provides accurate error data for subsequent time calibration and frequency adjustment.

Local Time Reference Unit: Based on high-performance crystal oscillators or atomic clocks, it generates and maintains stable and accurate local time, and completes time calibration and frequency adjustment according to the time difference measurement results.

Frequency Signal Distribution and Amplification Unit: Distributes and amplifies the high-stability frequency signals output by the frequency reference source to provide sufficient frequency drive capability for a large number of frequency-using equipment on the aircraft.

Time Difference Information Distribution Unit: Transmits the time difference data to each terminal system in the non-direct synchronization architecture.

Synchronous Signal Generation Unit: Generates standard IRIG-B (DC) time code signals and other synchronous pulse signals required by the avionic system to realize unified time distribution among all devices.

4. Key Technologies of Airborne Time and Frequency Synchronization

To meet the harsh environmental conditions of airborne platforms (high-speed movement, large temperature changes, strong vibration, complex electromagnetic interference, limited space and power consumption), airborne time and frequency synchronization systems must break through a number of key core technologies. These key technologies are the foundation of ensuring the high precision, high stability, and high reliability of the synchronization system. This chapter focuses on three key core technologies: low phase-noise and high anti-vibration crystal oscillator technology, high-precision time synchronization technology under high dynamic conditions, and wide-temperature, high anti-vibration, miniaturized rubidium atomic clock technology, and analyzes their working principles, technical challenges, and engineering implementation methods.

4.1. Low Phase Noise and High Anti-Vibration Crystal Oscillator Technology

The crystal oscillator is the core frequency source of the airborne time and frequency system, providing stable frequency signals for all airborne electronic equipment. The performance of the crystal oscillator directly determines the synchronization accuracy and stability of the entire time and frequency system. In the airborne environment, the equipment will be subjected to strong random vibration and impact (acceleration up to 10g or more), which will seriously deteriorate the phase noise index of the crystal oscillator and reduce the stability of time and frequency output. Therefore, low phase noise and high anti-vibration crystal oscillator technology is one of the most critical basic technologies in the airborne time and frequency synchronization system. The phase noise of the crystal oscillator directly affects the detection accuracy of radar and the positioning accuracy of passive positioning systems.

Phase noise is an important indicator to measure the stability of the crystal oscillator, which reflects the random fluctuation of the output frequency of the crystal oscillator. The lower the phase noise, the more stable the frequency output of the crystal oscillator. When the crystal oscillator is subjected to external random vibration, the vibration frequency will be modulated to the output frequency of the crystal oscillator, resulting in additional modulation sidebands in the output spectrum, which significantly increases the phase noise. This phenomenon is called vibration-induced phase noise, which is the main factor affecting the performance of the crystal oscillator in the airborne environment. Vibration-induced phase noise will cause frequency jitter, which further affects the synchronization accuracy of the entire system.

The phase noise variation of the crystal oscillator under random vibration can be expressed by the following formula:

$$\pounds\,(f\nu) = (G(f\nu)/2)(\Gamma f o/f\nu)2$$

Where:

G(ν) is the acceleration spectral density of random vibration, whose unit is $\text{m}^2/\text{s}^4/\text{Hz}$;

o is the nominal operating frequency of the crystal oscillator, whose unit is Hz;

ν is the vibration frequency, whose unit is Hz;

Γ is the acceleration sensitivity of the crystal resonator, whose unit is $\text{Hz}/(\text{m}/\text{s}^2)$.

It can be seen from the formula that the phase noise deterioration caused by vibration is closely related to the acceleration sensitivity of the crystal, the vibration frequency, the vibration spectral density, and the working frequency of the crystal oscillator. To reduce the influence of vibration on phase noise, two technical approaches are mainly adopted at home and abroad: active vibration reduction and passive vibration reduction. These two approaches are often used together to achieve the best anti-vibration effect.

Active vibration reduction: Develop crystal resonators with extremely low acceleration sensitivity to reduce the frequency modulation effect caused by vibration from the source. The acceleration sensitivity of the crystal resonator is determined by its material, structure, and processing technology. By optimizing the crystal material (such as using high-purity quartz crystal), improving the crystal cutting angle, and adopting advanced processing technology (such as polishing, cleaning), the acceleration sensitivity of the crystal resonator can be reduced to less than 1×10^{-9} $\text{Hz}/(\text{m}/\text{s}^2)$. However, the development of low acceleration sensitivity crystal resonators has high technical difficulty and high cost, and is currently mainly used in high-end airborne equipment. For example, the low acceleration sensitivity crystal resonator developed by a domestic manufacturer has an acceleration sensitivity of 5×10^{-10} $\text{Hz}/(\text{m}/\text{s}^2)$, which can effectively reduce vibration-induced phase noise.

Passive vibration reduction: Adopt optimized mechanical vibration isolation structure design to reduce the vibration acceleration transmitted to the crystal oscillator. This method is simple in implementation, low in cost, and widely used in engineering applications. The mechanical vibration isolation structure is usually composed of a vibration isolation base, a damping layer, and a fixing device. The vibration isolation base is made of high-damping materials (such as rubber, foam), which can absorb and attenuate the vibration energy. The damping layer is used to reduce the resonance of the vibration isolation structure, avoiding the amplification of vibration in a certain frequency band. By installing a high-performance vibration isolation device for the crystal oscillator, the vibration energy in the frequency band of 20 Hz to 2000 Hz (the main vibration frequency band of airborne platforms) can be greatly attenuated, the vibration acceleration transmitted to the crystal oscillator can be reduced by more than 90%, so that the crystal oscillator can work stably under strong vibration conditions. The vibration isolation device usually adopts a multi-layer structure to further improve the vibration isolation effect.

In addition to vibration resistance, the crystal oscillator also needs to have good wide-temperature adaptability. The airborne environment has a large temperature change range (from -45°C to 70°C), and the temperature change will cause the frequency drift of the crystal oscillator, affecting its stability. Therefore, the low phase-noise and high anti-vibration crystal oscillator usually adopts a temperature-compensated crystal oscillator (TCXO) or an oven-controlled crystal oscillator (OCXO). TCXO uses temperature compensation circuits to offset the frequency drift caused by temperature changes, with a frequency stability of 1×10^{-9} to 1×10^{-10}; OCXO uses an oven to keep the crystal oscillator at a constant temperature, with a higher frequency stability of 1×10^{-11} to 1×10^{-12}, which is suitable for high-precision airborne applications. OCXO is usually used in scenarios with high precision requirements, while TCXO is used in scenarios with limited power consumption and volume.

At present, the international representative manufacturers of high-performance anti-vibration crystal oscillators include Rakon (New Zealand), Vectron (USA), FEI (USA), Wenzel (Germany), etc. The domestic representative product is ChenDu Spaceon Electronics..Ltd' SOXO14V series. The performance comparison of typical products is as shown in the Table 1.:

Table 1. Performance Comparison of Anti-Vibration OCXOs/TCXOs

Manufacturer	Product Model	Nominal Frequency	Package Size (mm^3)	Vibration Phase Noise	Temperature Range	Frequency Stability
VECTRON	OX-990	100MHz	58×48×27	-145dBc/Hz@1kHz	-40℃~70℃	1×10^{-11}
RAKON	ULN HF C	100MHz	59.2×48.2×27	-145dBc/Hz@1kHz	-40℃~70℃	1×10^{-11}
Spaceon Electronics	SOXO14V	100MHz	38×38×20	-145dBc/Hz@1kHz	-45℃~70℃	5×10^{-12}

Products of VECTRON and RAKON have large size and high price (up to 160,000 RMB per piece), and cannot be customized for special vibration conditions. Domestic products have reached the international advanced level in key indicators, with smaller size and higher cost performance, and can meet the needs of domestic military aircraft.

The actual measured phase noise results of the low phase noise and high anti-vibration crystal oscillator are shown in Figure 2.

Figure 2. Measured Phase Noise Results of Low Phase Noise Anti-Vibration Crystal Oscillator

4.2. High-Precision Time Synchronization Technology

High-precision time synchronization under high dynamic conditions is the core technology to ensure the combat performance of airborne radar networking and passive positioning systems. The time synchronization accuracy of combat aircraft is jointly determined by three factors: absolute time accuracy, real-time delay correction, and autonomous holdover capability.

The high-precision time synchronization design of airborne equipment mainly includes two core technologies:

Intelligent phase-locked frequency synchronization technology: Realizes high-stability frequency locking between systems, so that the frequency of the whole machine can be traced back to the satellite reference frequency, ensuring frequency consistency.

High-precision time delay correction technology: Through precise time difference measurement, IODELAY digital fine-tuning, adaptive loop bandwidth adjustment and other means, the time delay can be compensated with high precision, and the delay correction resolution can be better than **80 ps**.

Through a large number of simulated flight tests and actual flight verification, the master-slave time synchronization accuracy of the airborne time and frequency system can reach **with in 1 ns**, which fully meets the most stringent requirements of airborne passive positioning and radar networking. The measured results of time synchronization is shown in figure3.

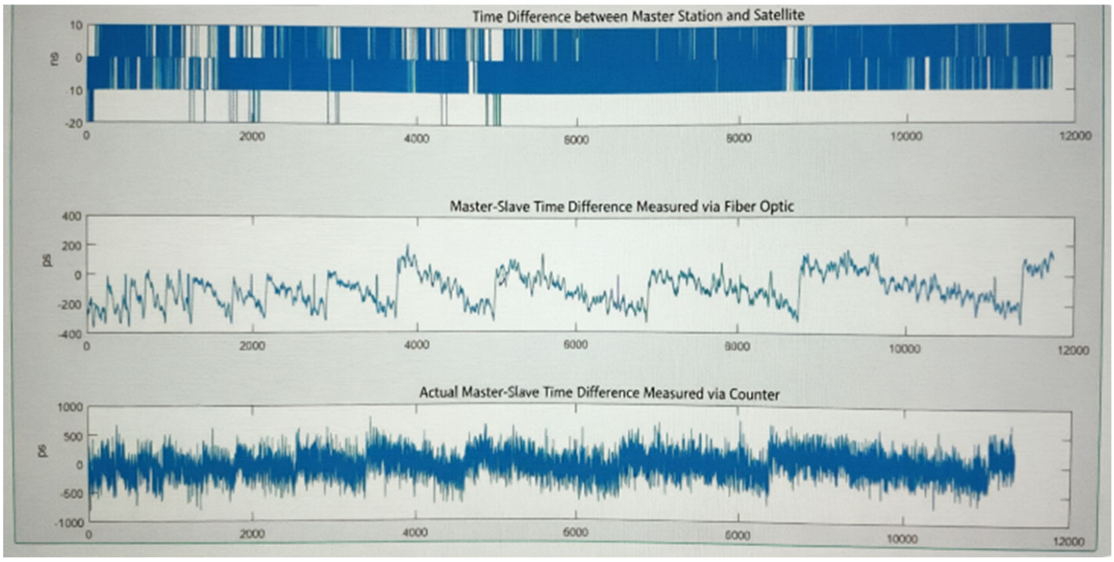

Figure 3. Measured Results of Time Synchronization

4.3. Wide-Temperature, High Anti-Vibration, Miniaturized Rubidium Atomic Clock Technology

Rubidium atomic clock is a high-performance frequency reference device using the atomic energy level transition characteristics of ^{87}Rb. Its central transition frequency is 6834.6875 MHz. By locking the oven-controlled crystal oscillator to the atomic transition frequency through the phase-locked loop, the crystal oscillator has the ultra-high stability and accuracy of atomic frequency, Composition of the working principle of the Rubidium Atomic Clock is shown in Figure4.

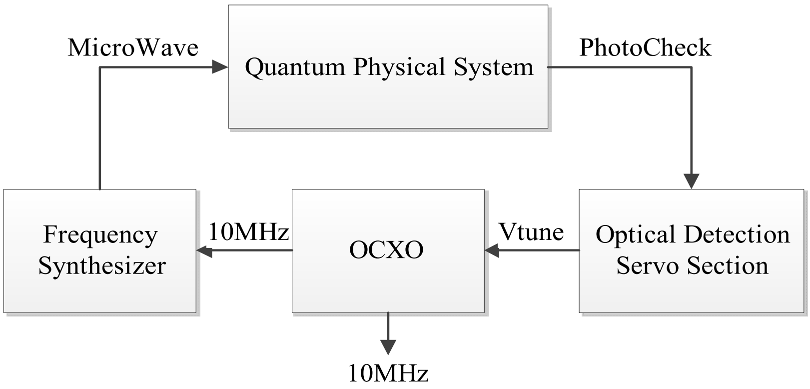

Figure 4. Composition of the Working Principle of the Rubidium Atomic Clock

Rubidium atomic clock has the advantages of high frequency stability, high accuracy, low aging rate, small volume, and low power consumption. It is the most widely used atomic clock in the military field. For airborne platforms, the traditional rubidium atomic clock has problems such as large volume, poor wide-temperature adaptability, and weak anti-vibration ability. Domestic CPT atomic clocks (chip-scale atomic clocks) cannot meet the requirements of short-term stability, aging rate, and temperature characteristics. High-end foreign military rubidium atomic clocks are under strict embargo. Therefore, it is urgent to develop a **wide-temperature, high anti-vibration, miniaturized rubidium atomic clock** suitable for airborne environments.

The airborne rubidium atomic clock must meet the following harsh environmental indicators:

Through a large number of tests and verifications, the performance of the independently developed airborne rubidium atomic clock is as follows:

Disciplined frequency accuracy: **8.5×10^{-13}, shown in figure5**;

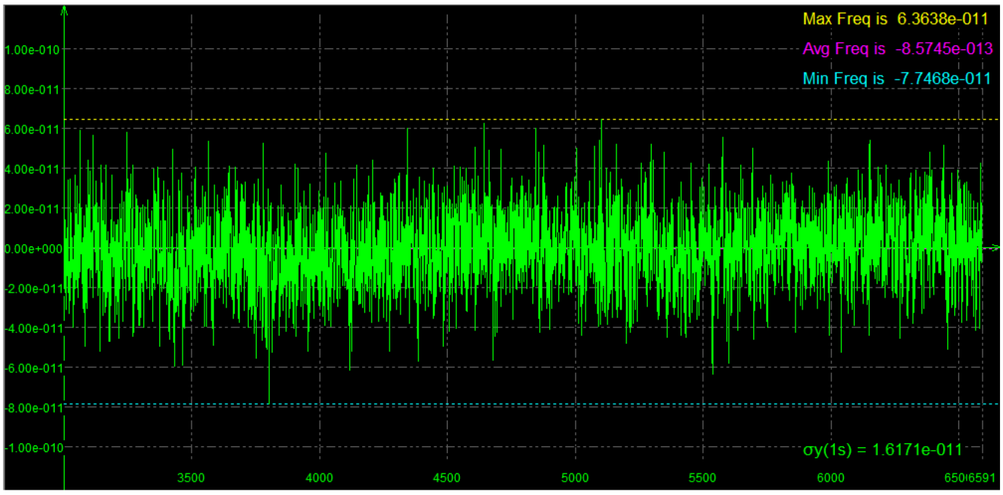

Figure 5. Measured Results of Rubidium Atomic Clock Disciplining

Frequency accuracy in actual flight state: **1.15×10^{-10}, shown in figure 6**;

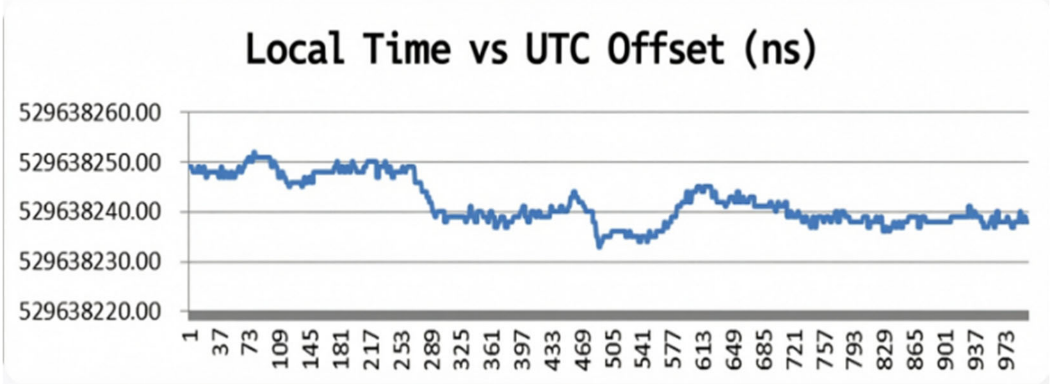

Figure 6. Measured Results in Flight State

The measured results of the frequency accuracy temperature curve under the condition of -45℃ to 70℃ are shown in Figure 7.

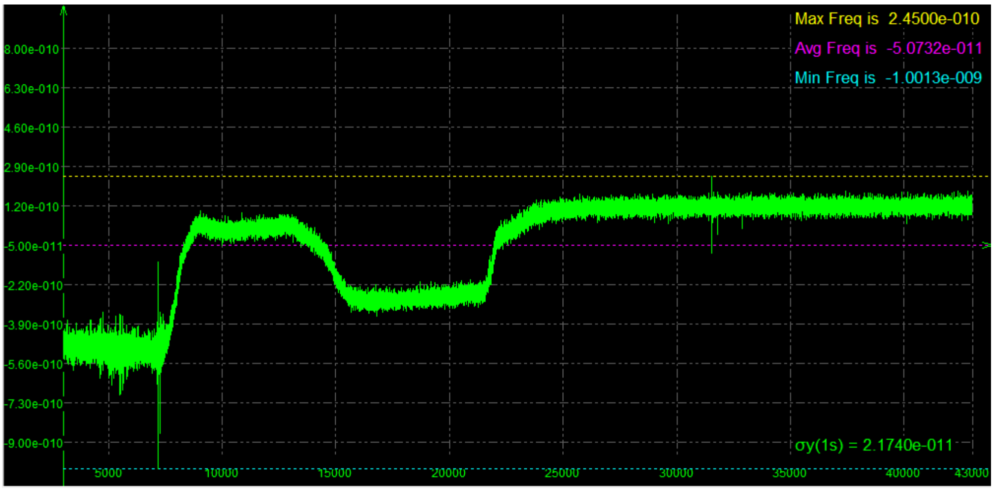

Figure 7. Measured Results of Frequency Accuracy vs. Temperature Curve

Anti-vibration capability: above 10 g random vibration. The measured results of the frequency accuracy of the rubidium atomic clock under random vibration conditions are shown in Figure 8

Stable performance under wide temperature and strong vibration conditions.

This technology has broken through the foreign blockade and filled the domestic gap, providing a core device support for the airborne time and frequency system.

5. Development Trend of Airborne Time and Frequency Synchronization Technology

5.1. Multi-Crystal Acceleration Mutual Compensation Technology

Multi-crystal acceleration mutual compensation is a new type of active anti-vibration technology. By integrating multiple crystal resonators in the same oscillator and reasonably matching their acceleration sensitivity vectors, the acceleration sensitivity in different directions can be offset from each other, thereby greatly reducing the phase noise deterioration caused by vibration.

Theoretically, the ideal four-crystal mirror compensation scheme can completely offset the acceleration sensitivity in X, Y, Z three axes, and realize zero influence of vibration on phase noise. However, due to the discreteness of crystal parameters, it is difficult to achieve complete matching in engineering. Therefore, the dual-crystal pairing compensation scheme is more practical, with a success rate 16 times that of the four-crystal scheme, which can significantly optimize the dynamic phase noise and is suitable for high-performance airborne applications.

5.2. Chip-Scale Optical Clock Technology

Chip-scale optical clock is a revolutionary new-generation time and frequency device. It uses the optical frequency transition of atoms in the micro-cell on the chip, and converts the ultra-high optical frequency into a usable microwave frequency through the on-chip optical frequency comb. The core chip power consumption is only **275 mW**, with the advantages of ultra-small size, ultra-low power consumption, and ultra-high stability.

In the future, chip-scale optical clocks are expected to replace traditional crystal oscillators and atomic clocks, and become the core frequency source of airborne, satellite, and portable devices. It is an important development direction of next-generation airborne time and frequency technology.

6. Conclusion

With the continuous development of modern warfare towards informatization, networking, and systematization, time and frequency synchronization technology has become an important basic support to improve the combat effectiveness of combat aircraft. Airborne time and frequency synchronization system, as an important public resource of integrated avionic systems, provides key technical support for tactical applications such as airborne information fusion, radar networking, passive positioning, and system-level applications such as network-centric warfare.

This paper systematically studies the airborne time and frequency synchronization technology, system architecture, key core devices, and engineering implementation methods. Aiming at the harsh environmental requirements of high vibration, wide temperature, high dynamic, and strong interference of airborne platforms, key technologies such as low phase noise anti-vibration crystal oscillator, high-precision time synchronization, and wide-temperature miniaturized rubidium atomic clock have been broken through. The developed airborne time and frequency equipment has been verified by a large number of tests and actual flights. The results show that the equipment has excellent time synchronization accuracy and frequency stability under harsh airborne environmental conditions, can provide high-performance time and frequency signals for various systems of combat aircraft, and effectively supports the improvement of China's military aviation combat capability.

In the future, with the further development of multi-crystal compensation, chip optical clock, autonomous timekeeping, and anti-interference technology, airborne time and frequency synchronization system will develop towards higher precision, smaller volume, lower power consumption, stronger environmental adaptability, and higher reliability, and will play an increasingly important role in the field of national defense and military.

7. Conflict of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

All authors confirm that there are no conflicts of interest, including but not limited to financial, personal, professional, or other relationships that might bias the research or its presentation. No funding sources or financial supports have influenced the design of the study, the collection, analysis, and interpretation of data, or the writing of the manuscript.

Any potential conflicts of interest that could be perceived as affecting the objectivity of this work have been fully disclosed and resolved prior to the submission of this manuscript.

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