Improvement of frequency source phase noise reduction design under vibration condition

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Abstract. Reasonable vibration reduction design is an important way to achieve low phase noise index of airborne frequency source output signal. Aiming at the problem of phase noise deterioration of an airborne frequency source under random condition, this paper proposes to improve the vibration reduction mode crystal oscillator and reduce the distance between the barycenter of frequency source and crystal oscillator vibration based on the analysis of the relationship between the frequency source and the phase noise of output signal. Experimental results show that the active noise control system achieves 62dB phase noise compensation under the random vibration of $0.04 \sim 0.1 g^2$/Hz amplitude range and 5~2000Hz frequency range.

1 Introduction

With the continuous development of microwave radio frequency technology, the requirement of microwave system index is also gradually increased, so the requirement of spectrum purity of microwave frequency source is particularly prominent. In the application of the airborne platform, the frequency source is often affected by the random vibration of the airborne platform, and the random vibration frequency of the aircraft engine will superimpose on the output signal of the frequency source, which will worsen the phase noise. Therefore, the development of low phase noise, high stability and high reliability frequency source and its performance test have become important contents in the development of microwave system. The quartz crystal oscillator is the most commonly used frequency source reference. Under the influence of random vibration caused by acceleration, the output signal may appear frequency offset, and the phase noise in the spectrum will deteriorate correspondingly [1]. The traditional method to reduce the sensitivity of crystal oscillator acceleration is to use mechanical buffer measures, which can effectively reduce the amplitude of high frequency vibration above 850Hz, but may lead to the increase of low

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frequency vibration amplitude [2]. Based on the microwave frequency source in the application environment of the airborne platform, this paper proposes to replace the mechanical vibration isolation type of constant temperature crystal oscillator with the dual crystal acceleration compensation type of constant temperature crystal oscillator, and move the barycenter of the frequency source to the position of the crystal oscillator, which reduces the acceleration sensitivity and acceleration amplitude of the frequency source, and can effectively improve the phase noise of the frequency source output frequency under random vibration conditions. The experimental results show that the improvement effect is obvious, and the maximum phase noise optimization of 62dB can be achieved under the condition of random sweeping vibration in the vibration amplitude of 0.04~0.1g²/Hz and frequency range of 5~2000Hz.

2 Frequency source introduction

This frequency source selects a 100MHz anti-vibration type constant temperature crystal refresh reference source. Through frequency synthesis, various clock and frequency marker signals are generated. The basic block diagram of the frequency source is shown in Fig.1.
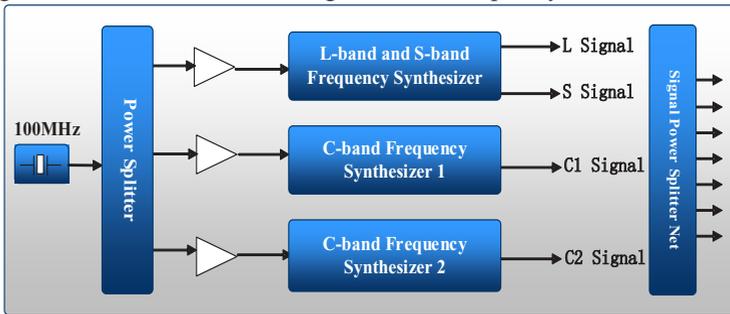

Fig. 1. Basic block diagram of frequency source.

Here, typical signals in several frequency bands are selected as examples for phase noise analysis, including L-band frequency 1380MHz, S-band frequency 2400MHz, C-band frequency 6000MHz and 7350MHz. The block diagram of frequency source circuit is shown in Fig.2.
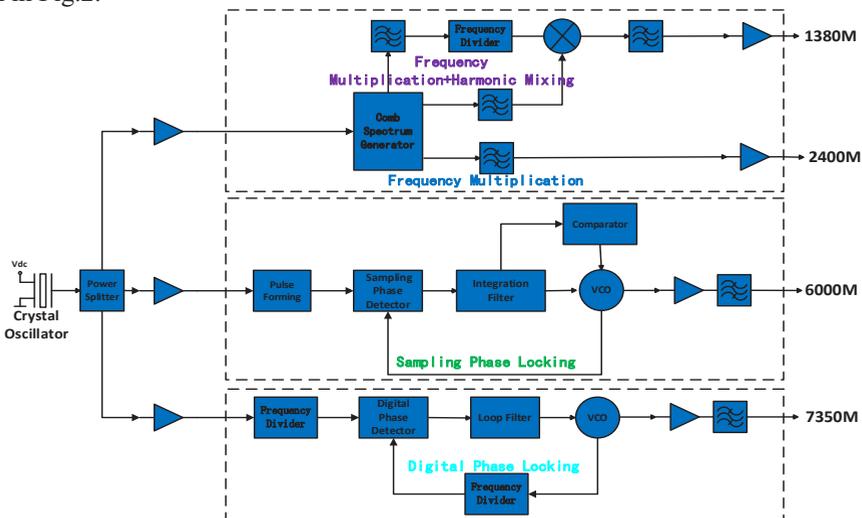

Fig. 2. Block diagram of frequency source circuit.

Synthesis methods for each frequency include:

The 100MHz signal generated by the crystal oscillator is doubled by the comb spectrum generator to take the harmonics 900MHz and 1200MHz, of which 900MHz is divided by 5 frequencies to produce 180MHz signal, and then mixed with 1200MHz to filter and amplify the 1380MHz continuous wave signal. The coherent direct synthesis method of active frequency doubling and harmonic mixing is adopted.

2400MHz continuous wave signal is obtained from 100MHz signal generated by crystal oscillator by frequency doubling filter of comb generator, which is synthesized by coherent direct synthesis method with active frequency doubling.

C-band C1 signal 6000MHz continuous wave signal is obtained from 100MHz signal generated by crystal oscillator by sampling phase-locked frequency doubling, which is synthesized by analog lock-phase synthesis method.

C-band C2 signal 7350MHz continuous wave signal is obtained from 100MHz signal generated by crystal oscillator through digital phase discrimination and phase lock frequency doubling, which is synthesized by digital lock method.

3 Vibration condition

The frequency source and the power supply share a bracket, and are installed together in the cabin of a jet aircraft, which has the characteristics of high altitude, low speed, long endurance, etc. The bracket is shown in Fig.3. Installation position of the Bracket is shown in Fig.4, and the random vibration of the aircraft is mainly caused by engine noise, aerodynamic turbulence along the outside of the aircraft, landing and taxiing, and taking off. The random vibration of the aircraft is vertical, transverse and longitudinal. The energy of random vibration on the cargo hold floor of jet aircraft is mainly distributed in the frequency range from 1.6Hz to 2000Hz, with peaks near the low frequency of 8-10Hz and the high frequency of 400Hz. After standardized processing, the spectrum of acceleration spectral density is shown in Fig.5 [3].

Power Source Installation Position

Frequency Source Installation Position

Fig. 3. The bracket.
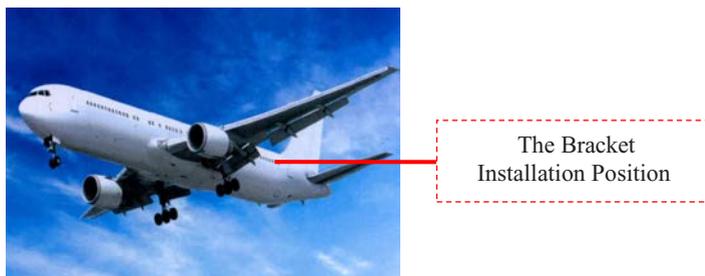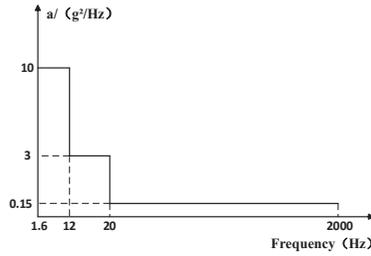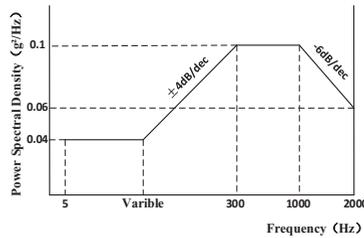

The Bracket Installation Position

Fig. 4. Installation position of the bracket.

Fig. 5. Spectral density of acceleration of jet aircraft.

The vibration environment of the frequency source installed on the jet aircraft mainly comes from three aspects: the engine noise stimulates the aircraft structure; Aerodynamic turbulence along the outside of the aircraft structure; The vibration of collective structure caused by maneuvering flight, aerodynamic buffeting, landing and taxiing of aircraft [3].

The vibration caused by engine noise is generally dominant when the aircraft is flying at low dynamic pressure, such as subsonic flight at low altitude and supersonic flight at high altitude. The vibration caused by aerodynamic turbulence generally plays a major role in the flight of aircraft at low altitude transonic speed and supersonic speed at various altitudes. The random vibration spectrum of the frequency source installed on the jet is shown in Fig.6 [3].

Fig. 6. Random vibration music chart of frequency source.

The frequency source will carry out random sweeping vibration according to the above random vibration spectrum 5Hz~2000Hz~5Hz. The random vibration test site is shown in Fig.7.
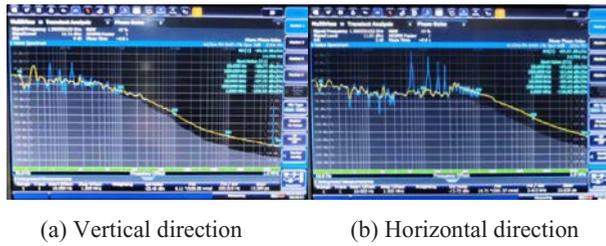

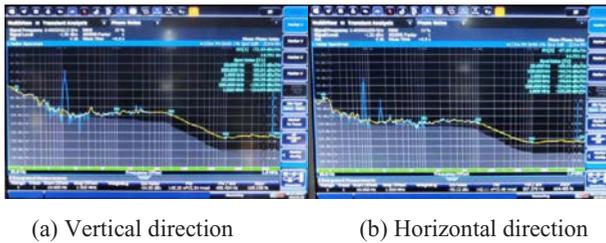(a) Horizontal X axis   (b) Horizontal Y axis   (c) Vertical Z axis

Fig. 7. Random vibration test site.

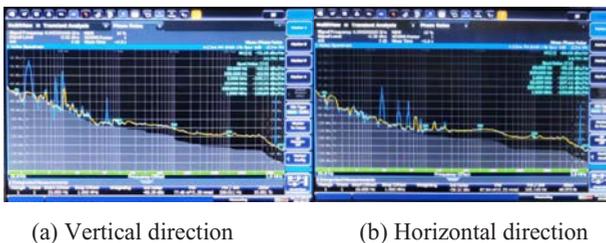## 4 Dynamic phase noise before frequency source optimization and improvement

When the frequency source is used for random vibration test of sweeping frequency before improvement, the phase noise of signal output is shown in Fig.8~11, and the test indicators are shown in Table 2.
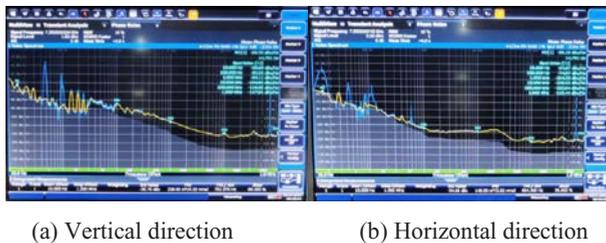
(a) Vertical direction   (b) Horizontal direction

Fig. 8. Dynamic phase noise of 1380MHZ before improvement.

(a) Vertical direction   (b) Horizontal direction

Fig. 9. Dynamic phase noise of 2400MHz before improvement.

(a) Vertical direction   (b) Horizontal direction

Fig. 10. Dynamic Phase Noise of 6000MHz before Improvement.

(a) Vertical direction   (b) Horizontal direction

Fig. 11. Dynamic phase noise of 7350MHz before improvement.

As can be seen from Fig.8~11, the sweep vibration frequency of the shaking table will be superimposed on the phase noise curve of the measured signal in real time, which makes the phase noise of the measured frequency deteriorate under vibration conditions.

5 Frequency source output frequency noise reduction analysis and improvement

5.1 Phase noise reduction analysis

The frequency source has a built-in thermostatic crystal oscillator and its output reference frequency is 100MHz. Crystal oscillator is a piezoelectric vibration sensitive device, and its

output phase noise directly affects the phase noise of each frequency point of the final output of the frequency source.

Table 1. Dynamic phase noise at each frequency point of the output of the frequency source before improvement.

Number	Frequency	Vibration Direction	Phase noise measured value
1	1380MHz	Vertical direction	-57dBc/Hz@1kHz -128dBc/Hz@1MHz
		Horizontal direction	-57dBc/Hz@1kHz -116dBc/Hz@1MHz
2	2400MHz	Vertical direction	-96dBc/Hz@1kHz -124dBc/Hz@1MHz
		Horizontal direction	-97dBc/Hz@1kHz -122dBc/Hz@1MHz
3	6000MHz	Vertical direction	-105dBc/Hz@1kHz -133dBc/Hz@1MHz
		Horizontal direction	-107dBc/Hz@1kHz -133dBc/Hz@1MHz
4	7350MHz	Vertical direction	-84dBc/Hz@1kHz -117dBc/Hz@1MHz
		Horizontal direction	-104dBc/Hz@1kHz -115dBc/Hz@1MHz

The output signal of an ideal constant temperature crystal oscillator can be simulated as a pure sine wave, and the model is shown in Equation (1):

$$f(\mathrm{t}) = \mathrm{V}_0 \cdot \sin(2\pi f_0 \cdot t) \tag{1}$$

where, V_0 is the nominal amplitude, f_0 is the nominal frequency, here is 100MHz. In fact, there are always some deviations in the amplitude and frequency of the output signal of the isothermal crystal oscillator, which are included in the model to obtain a model of the actual isothermal crystal oscillator output signal as shown in equation (2):

$$f(\mathrm{t}) = [\mathrm{V}_0 + \varepsilon(\mathrm{t})] \cdot \sin[2\pi f_0 \cdot t + L_{f_0}(\mathrm{t})] \tag{2}$$

where, $\varepsilon(t)$ is amplitude noise and $L_{f_0}(\mathrm{t})$ is phase noise. In practical application, the influence of amplitude noise can be reduced to a negligible degree by adding an amplitude stabilizer device, so $\varepsilon(t)$ in equation (2) can be omitted, so the model shown in equation (2) can be simplified to equation (3):

$$f(\mathrm{t}) = \mathrm{V}_0 \cdot \sin[2\pi f_0 \cdot t + L_{f_0}(\mathrm{t})] \tag{3}$$

Under the condition of random sweep frequency vibration, the phase noise of crystal vibration is shown in equation (4):

$$L_{f_0} = 20\log\left(\vec{\Gamma} \cdot \vec{A} \cdot \frac{f_0}{f_V(t)} \cdot \sqrt{\frac{G(f_V(t))}{2}} \right) \tag{4}$$

where, L_{f_0} is the phase noise of the crystal vibration, $\vec{\Gamma}$ is the acceleration sensitivity vector, $\vec{A}$ is the acceleration amplitude value, f_0 is the frequency of the crystal vibration,

$f_V(t)$ is the phase noise offset carrier frequency of the crystal vibration, and $G(f_V(t))$ is the acceleration energy spectral density under this vibration frequency [4-6].

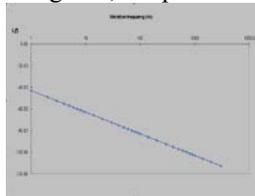Acceleration sensitivity vector $\overline{\Gamma}$ amplitude is shown in equation (5):

$$\left|\overline{\Gamma}\right| = \sqrt{\Gamma_X^2 + \Gamma_Y^2 + \Gamma_Z^2} \tag{5}$$

where, Γ_X, Γ_Y, Γ_Z, are the acceleration sensitivity vectors of the three axes X, Y and Z respectively.
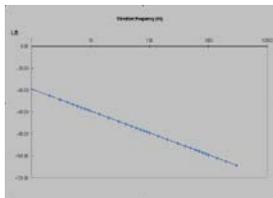
Acceleration amplitude vector $\overline{A}$ is shown in equation (6):

$$\left|\overline{A}\right| = \sqrt{A_X^2 + A_Y^2 + A_Z^2} \tag{6}$$

According to the simulation calculation of the steady-state phase noise of 100MHz constant temperature crystal oscillator and equation (1), when the power spectral density of random vibration is 0.04g²/Hz, the phase noise curve is shown in Fig.12. When the random vibration power spectral density is 0.1g²/Hz, the phase-noise curve is shown in Fig.13.

Fig. 12. 0.04g²/Hz dynamic phase-noise simulation curve of 100MHz constant temperature crystal oscillator.

Fig. 13. 0.1g²/Hz Dynamic phase-noise simulation curve of 100MHz constant temperature crystal oscillator.

Under the condition of random vibration, the phase noise of each frequency point output by the frequency source is shown in equation (7):

$$L_{f_1} = 20\log\left(\vec{\Gamma}\cdot\vec{A}\cdot\frac{N\cdot f_0}{f_V(t)}\cdot\sqrt{\frac{G(f_V(t))}{2}}\right) \tag{7}$$

where, L_{f_1} is the phase noise of the output frequency of the frequency source, f_1 is the output frequency of the frequency source, that is $f_1 = N\cdot f_0$. In this paper, the output of the crystal oscillator is 100MHz, the signal frequencies are 1380MHz, 2400MHz,

6000MHz and 7350MHz respectively, and the corresponding N is 13.8, 24, 60 and 73.5 respectively. Equation (7) can be simplified to equation (8):
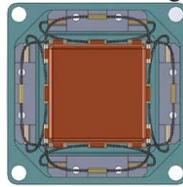
$$L_{f_1} = L_{f_0} + 20\log N \tag{8}$$

According to the simulation results, when the random vibration power spectral density is 0.04~0.1g²/Hz, the phase noise of each signal output by the frequency source can be inquired into the dynamic phase noise value of the constant temperature crystal oscillator in Fig. 16 and Fig. 17, and then calculated by equation (8). From equation (7) and equation (8), it can be seen that under the determined condition of random sweeping vibration, that is $f_V(t)$, 5Hz~2000Hz, the acceleration energy spectral density $G(f_V(t))$ has been determined. At this time, the influence of vibration on the phase noise of the frequency source can be reduced by reducing $\overline{\Gamma}$ and $\overline{A}$ [7-9].

5.2 Phase noise reduction improvement

5.2.1 Improvement of crystal vibration damping mode

The original frequency source is the passive acceleration vibration reduction isolated constant temperature crystal oscillator. The main purpose of passive acceleration isolation is to reduce the transmission of external vibration energy to the crystal vibration. There are many kinds of technical measures for passive acceleration vibration reduction and isolation, including steel wire rope vibration reduction, rigid beam arm, spring vibration reduction, rubber cushion vibration reduction, silicone rubber vibration reduction. The thermostatic crystal oscillator originally selected here uses high-density stainless steel wire rope as vibration isolation material, and the internal vibration isolation structure diagram of the original thermostatic crystal oscillator is shown in Fig.14 [10, 11].

Fig. 14. Schematic diagram of internal vibration isolation structure of the original constant temperature crystal oscillator.

It is evident from Section 4 that the output frequency and phase noise of the mechanically damped thermostatic crystal oscillator, utilizing high-density stainless steel wire rope as a vibration isolation material, exhibit significant degradation under random vibration conditions compared to steady-state operation. This phenomenon arises due to the presence of multiple resonances within the random vibration frequency range of 5～2000Hz in these passive acceleration vibration isolation materials. As a result, their resonance frequencies cannot be effectively isolated from or mitigated within the 5～2000Hz range, necessitating alternative methods for reducing deterioration in crystal output frequency phase noise during random vibration conditions.

Furthermore, space constraints and high-intensity vibrational environments can lead to crystals impacting the inner walls of their enclosures, further contributing to degradation in crystal output frequency phase noise. The potential damage or reduction in lifespan of the crystals under such circumstances remains unpredictable.

In order to avoid the above situation, we abandon the thermostatic crystal oscillator with mechanical damping, and use twin crystal acceleration to compensate crystal vibration to improve the phase noise index of crystal vibration. The dual crystal acceleration compensation method is to select two crystals with equal acceleration sensitivity, and adopt the method of mirror installation to offset the frequency change and phase change caused by vibration to achieve compensation. Crystal pairing is shown in Fig.15 [12-14].
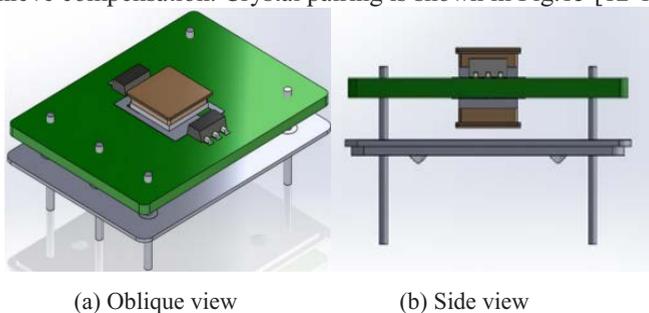

(a) Oblique view   (b) Side view

Fig. 15. Dual crystal acceleration compensation installation diagram.

5.2.2 Improvement of crystal vibration damping mode

Fig.16 shows the installation positions of components in the original module. The constant temperature crystal oscillator is located on the A side, the frequency standard component (weighing about 3300g) is located on the B side, and the center of mass is located in the middle of the frequency source box body.
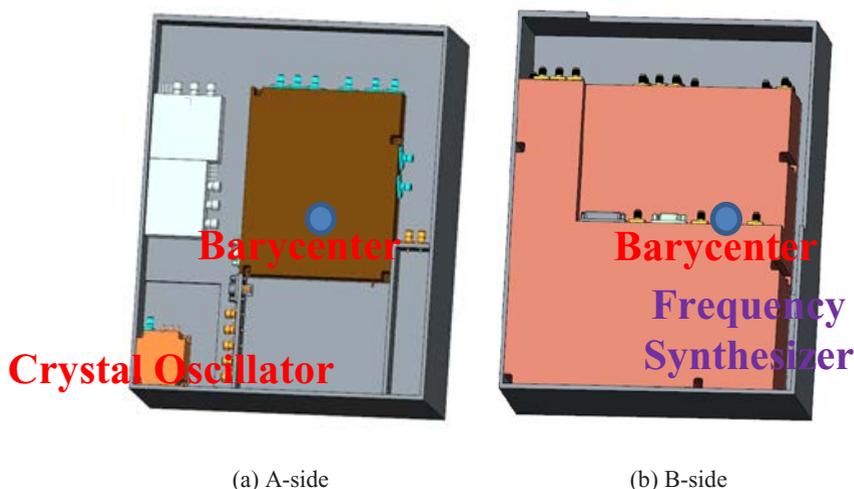

(a) A-side   (b) B-side

Fig. 16. Schematic diagram of installation positions of components inside the original frequency source.

Here, the weight of the frequency marker component can be reduced by making the barycenter of the frequency source move in the direction of the crystal oscillator while the installation position of the crystal oscillator remains unchanged, so as to achieve the purpose of reducing $\overline{A}$, so as to improve the phase noise index of the crystal oscillator. The weight of the improved frequency standard component is about 2650g, and the frequency source barycenter displacement diagram is shown in Fig.17.

Fig. 17. Schematic diagram of installation position and barycenter displacement of b-side frequency standard components of the improved frequency source.

6 The improved frequency source output frequency dynamic phase noise

During the random vibration test of the improved frequency source, the phase noise of the test output signal is shown in Fig.18~21, and the test indicators are shown in Table 2.

(a) Vertical direction   (b) Horizontal direction

Fig. 18. Improved 1380MHz dynamic phase noise.

(a)Vertical direction   (b)Horizontal direction

Fig. 19. Improved 2400MHz dynamic phase noise.

(a) Vertical direction   (b) Horizontal direction

Fig. 20. Improved 6000MHz dynamic phase noise.

(a) Vertical direction   (b) Horizontal direction

Fig. 21. Improved 7350MHz dynamic phase noise.

Table 2. Dynamic phase noise at each frequency output of the improved frequency source.

Number	Frequency	Vibration Direction	Phase noise measured value
1	1380MHz	Vertical direction	-119dBc/Hz@1kHz -140dBc/Hz@1MHz
		Horizontal direction	-119dBc/Hz@1kHz -140dBc/Hz@1MHz
2	2400MHz	Vertical direction	-104dBc/Hz@1kHz -130dBc/Hz@1MHz
		Horizontal direction	-102dBc/Hz@1kHz -129dBc/Hz@1MHz
3	6000MHz	Vertical direction	-108dBc/Hz@1kHz -137dBc/Hz@1MHz
		Horizontal direction	-108dBc/Hz@1kHz -137dBc/Hz@1MHz
4	7350MHz	Vertical direction	-112dBc/Hz@1kHz -124dBc/Hz@1MHz
		Horizontal direction	-111dBc/Hz@1kHz -124dBc/Hz@1MHz

7 Results and analysis

The comparison of phase noise test indexes of each frequency point of the frequency source output under random vibration conditions before and after improvement is shown in Table 3 below.

Table 3. Dynamic phase-noise comparison of each frequency point of frequency source output before and after improvement.

Number	Frequency	Vibration Direction	Improved pre-phase Noise	Improved Phase Noise	Improve Results
1	1380MHz	Vertical direction	-57dBc/Hz@1kHz -128dBc/Hz@1MHz	-119dBc/Hz@1kHz -140dBc/Hz@1MHz	62dBc@1kHz 12dBc@1MHz
		Horizontal direction	-57dBc/Hz@1kHz -116dBc/Hz@1MHz	-119dBc/Hz@1kHz -140dBc/Hz@1MHz	62dBc@1kHz 24dBc@1MHz
2	2400MHz	Vertical direction	-96dBc/Hz@1kHz -124dBc/Hz@1MHz	-104dBc/Hz@1kHz -130dBc/Hz@1MHz	8dBc@1kHz 6dBc@1MHz
		Horizontal direction	-97dBc/Hz@1kHz -122dBc/Hz@1MHz	-102dBc/Hz@1kHz -129dBc/Hz@1MHz	5dBc@1kHz 7dBc@1MHz
3	6000MHz	Vertical direction	-105dBc/Hz@1kHz -133dBc/Hz@1MHz	-108dBc/Hz@1kHz -137dBc/Hz@1MHz	3dBc@1kHz 4dBc@1MHz
		Horizontal direction	-107dBc/Hz@1kHz -133dBc/Hz@1MHz	-108dBc/Hz@1kHz -137dBc/Hz@1MHz	1dBc@1kHz 4dBc@1MHz
4	7350MHz	Vertical direction	-84dBc/Hz@1kHz -117dBc/Hz@1MHz	-112dBc/Hz@1kHz -124dBc/Hz@1MHz	28dBc@1kHz 7dBc@1MHz
		Horizontal direction	-104dBc/Hz@1kHz -115dBc/Hz@1MHz	-111dBc/Hz@1kHz -124dBc/Hz@1MHz	7dBc@1kHz 9dBc@1MHz

By comparing the above table, it can be seen that by reducing the acceleration sensitivity vector $\overline{\Gamma}$ and the acceleration amplitude vector $\overline{A}$ of the constant temperature crystal oscillator inside the frequency source, the output phase noise of the frequency source before and after the improvement is measured under random vibration conditions. Compared with the changes of phase noise before and after the frequency source, it can be seen that the phase noise index of the output signal of the frequency source is obviously improved, among which the phase noise of 1380MHz is improved 62dB@1kHz (vertical direction) /62dB@1kHz (horizontal direction). 2400MHz phase noise improvement 8dB@1kHz (vertical) /5dB@1kHz (horizontal); 6000MHz phase noise improvement 3dB@1kHz (vertical direction) /1dB@1kHz (horizontal direction); 7350MHz phase noise improvement 28dB@1kHz (vertical) /7dB@1kHz (horizontal).

8 Conclusion

This paper introduces an optimization and improvement method for noise suppression design of frequency source under random vibration condition. By analyzing the phase noise of each frequency point of the frequency source under the condition of random vibration, it is proposed to reduce the phase noise of the output signal of the frequency source by reducing the acceleration sensitivity vector and acceleration amplitude vector. The acceleration sensitivity vector is reduced by the acceleration compensation method of twin-crystal vibration, and the vibration sensitive device is placed in the constant temperature crystal vibration to reduce the acceleration amplitude vector. In the improved actual test results, under vibration conditions, the phase noise of the L-band signal at 1kHz reaches -119dBc/Hz, the phase noise of the S-band signal at 1kHz reaches -104dBc/Hz, and the phase noise of the C-band C1 signal at 1kHz reaches -108dBc/Hz. The phase noise of C2 signal at 1kHz reaches -112dBc/Hz. This design method is widely used in anti-vibration design, which helps to deeply analyze the mechanical characteristics of products, improve the design efficiency, and accelerate the process of realizing higher performance anti-vibration products.

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