Analysis of Two-stage Passive Vibration Isolation System for Crystal Oscillator at High-frequency Vibration

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***Abstract*—In this paper, the influence of vibrations on the crystal oscillator is analyzed in theory and the function of SSB phase noise under vibrations is given. To restrain high-frequency vibration effectively, a two-stage passive vibration isolation system for crystal oscillator is presented. This kind of vibration isolation system has low displacement transmissibility at high-frequency vibrations. The simulations and experiments are carried out. Experimental results show that at the random vibration whose acceleration spectral density is $0.05g^2$/Hz with frequency range 20Hz to 2000Hz, the SSB phase noise level of a 12.8MHz AT-cut crystal oscillator (whose acceleration sensitivity is about 2×10^{-9}/g) is reduced approximately from -100dBc/Hz to -120dBc/Hz at 1KHz offset by this vibration isolation system.**

I. INTRODUCTION

As the ultra stable standard frequency sources for modern communications, navigation, and radar systems, the crystal oscillator is very sensitive to vibrations[1][2]. In 1981, Raymond L. Filler reported the effect of vibration on crystal oscillator in his paper "The effect of vibration on frequency standards and clocks" [3].

Undergoing a single frequency harmonic vibration, the output frequency of crystal oscillator during vibration acceleration can be described as:

$$f(t)=f_0[1+S_g A(t)] \tag{1}$$

Where $A(t)$ is the vibration acceleration; f_0 is the carrier frequency of crystal oscillator experiencing zero acceleration; $f(t)$ is the carrier frequency of crystal oscillator in environment; S_g is the g-sensitivity.

The expression of phase noise in sinusoidal vibration environment is approximated as:

$$L_v^1(f_v)\approx 20\log(\frac{S_g f_0 A_p}{2f_v})dBc \tag{2}$$

Where f_v is the frequency of sinusoidal vibration in unit of Hz; A_p is the magnitude of sinusoidal acceleration vector in unit of g.

The formula of phase noise resulting from random vibration can be expressed as:

$$L_v^1(f_v)\approx 20\log(\frac{S_g f_0 A(f_v)}{2f_v})dBc \tag{3}$$

Where $A(f_v)=\sqrt{2G(f_v)}$ is the magnitude of sinusoidal equivalent acceleration of random vibration spectrum in 1Hz bandwidth at frequency f_v.

To provide the necessary spectral purity, a two-stage vibration isolation system for crystal oscillator is presented in this paper.

II. THEORY OF TWO-STAGE VIBRATION ISOLATION

The simple model of the two-stage vibration isolation system can be described as Fig.1 [4].

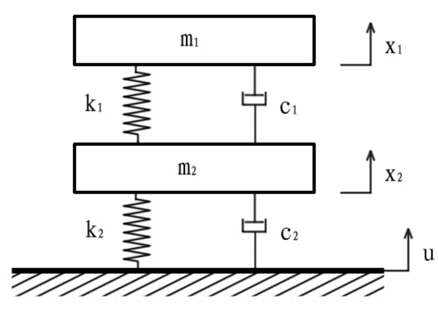

Figure 1. Simple model of the two-stage vibration isolation system

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Where m_1 is the mass of crystal oscillator, m_2 is the intermediate mass; k_1 , k_2 is stiffness coefficient of each stage; c_1, c_2 is damping coefficient of each stage; x_1, x_2 , u is vertical displacement of crystal oscillator, intermediate mass and the base.

The differential equations of motion can be described as below [5]:

$$\begin{aligned} &m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1x_1 - c_1\dot{x}_2 - k_1x_2 = 0 \\ &m_2\ddot{x}_2 + (c_1+c_2)\dot{x}_2 + (k_1+k_2)x_2 - c_1\dot{x}_1 - k_1x_1 = c_2\dot{u} + k_2u \end{aligned} \tag{4}$$

Then we can get the transfer function between $X_1(s)$ and $U(s)$:

$$G(s) = \frac{X_1(s)}{U(s)} = \frac{(c_1s+k_1)(c_2s+k_2)}{(m_1s^2+c_1s+k_1)[m_2s^2+(c_1+c_2)s+k_1+k_2]-(c_1s+k_1)^2} \tag{5}$$

By analyzing the amplitude-frequency characteristic of equation (5), we can get the function of displacement transmissibility:

$$T_D = \sqrt{\frac{(\alpha^2 - 4\zeta_1\zeta_2\alpha\bar{\omega}_1^2)^2 + \bar{\omega}_1^2(2\zeta_1\alpha^2 + 2\zeta_2\alpha)^2}{A^2+B^2}} \tag{6}$$

Where:

$$A = \bar{\omega}_1^4 - \bar{\omega}_1^2(\alpha^2 + 4\zeta_1\zeta_2\alpha + \mu + 1) + \alpha^2$$
$$B = \bar{\omega}_1^3(2\zeta_2\alpha + 2\zeta_1\mu + 2\zeta_1) - \bar{\omega}_1(2\zeta_1\alpha^2 + 2\zeta_2\alpha)$$
$$\mu = m_1/m_2$$

$$\bar{\omega}_1 = \omega/\omega_1$$
$$\alpha = \omega_2/\omega_1$$
$$\omega_1^2 = k_1/m_1$$
$$\omega_2^2 = k_2/m_2$$
$$\zeta_1 = c_1/2\sqrt{k_1m_1}$$
$$\zeta_2 = c_2/2\sqrt{k_2m_2}$$

When $\zeta_1, \zeta_2 << 1$, $\bar{\omega}_1 >> 1$:

$$T_D \approx \frac{\omega_1^2 \cdot \omega_2^2}{\omega^4} = \frac{k_1k_2}{m_1m_2\omega^4} \tag{7}$$

III. PARAMETERS DETERMINATION AND SIMULATION

The damping coefficient of normal steel spring whose diameter of wire less than 1mm is approximate to $0.01\text{N}\cdot\text{S/m}$ [6]. The mass of crystal oscillator m_1 is 0.004kg. From equation (6) and (7) we can see that by decreasing the value of k_1, k_2, or increasing the value of m_1, m_2, we can decrease the displacement transmissibility. Meanwhile, the size of vibration isolator will also increase. On the other hand, high transmissibility is observed at two natural frequencies ω_{n1} and ω_{n2}, rather than at one resonance frequency for the system with a single-stage isolator. The frequency ratio ω_{n2}/ω_{n1} will advantageously be a minimum (thus ω_{n2} will appear to be the closest to ω_{n1}) when the stiffness ratio $\delta = \frac{k_2}{k_1} = 1 + \frac{m_2}{m_1}$.

Consider about the influences mentioned above, we finally determined the parameters as:

$$k_1 = 53(N/m)$$
$$m_1 = 0.004(kg)$$
$$k_2 = 212(N/m)$$
$$m_2 = 0.016(kg)$$
$$c_1 = c_2 = 0.01(N \cdot s/m)$$

Substitute these parameters in equation (5) and (6), the transfer function and the displacement transmissibility function of vibration isolation system is determined. Simulate the displacement transmissibility of the system by MATLAB. The result of simulation is shown in Fig.2.

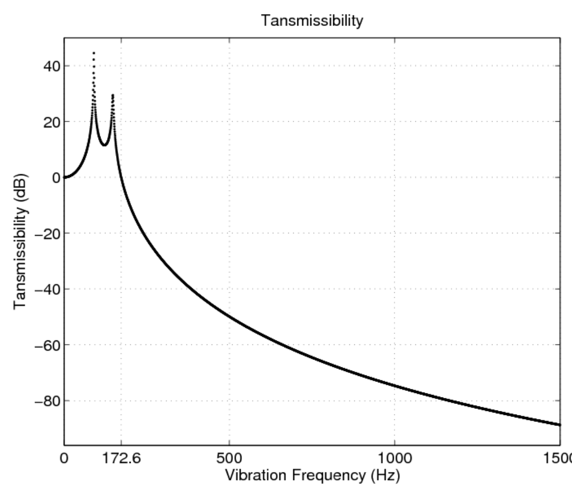

Figure 2. The displacement transmissibility of system (Processed by MATLAB)

According to Fig.2, when the vibration frequency is lower than 172.6Hz, the vibration isolation system does not decrease the influence of the vibration on the crystal oscillator. The vibration isolation system begin to work effectively when the vibration frequency higher than 172.6Hz, and the displacement transmissibility decreases fast with the increasing of vibration frequency. According to equation (7), transmissibility decreases as the fourth power of the vibration frequency at high vibration frequencies [4].

IV. EXPERIMENTAL PROCEDURE

The scheme of measurement system for dynamic phase noise is shown in Fig.3.

The measurement procedure can be described as follows, first, the vibration control computer output the control signal to the power amplifier according to the given vibration spectrum; next the power amplifier output the excitant current to the shaker to generate excitant force, and the accelerometer composed the feedback loop of the vibration control subsystem; at last, an Agilent E5052B signal source analyzer measured the phase noise under vibration.

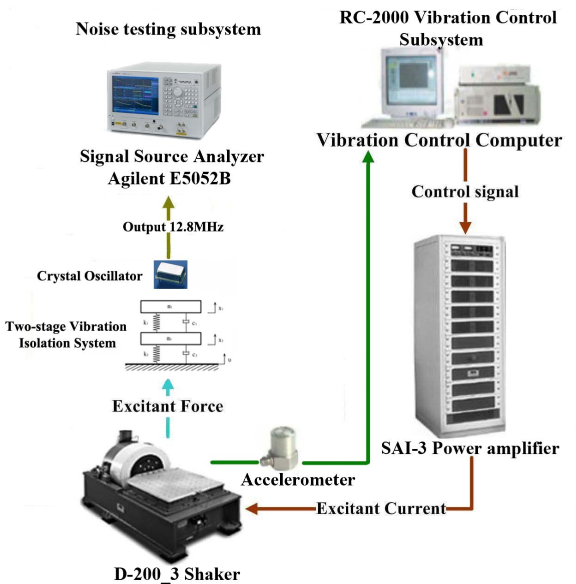

Figure 3. scheme of measurement system for dynamic phase noise

To find out how the effect of vibration isolation system is, two sets of experiments are carried out. The experimental environment is at the random vibration whose acceleration spectral density is $0.05g^2$/Hz with frequency range 20Hz to 2000Hz, and the experimental object is a 12.8MHz AT-cut crystal oscillator whose acceleration sensitivity is about $2\times10^{-9}/g$. First, in the random vibration environment, the phase noise of crystal oscillator without isolator is measured; and in the same vibration environment, the phase noise of crystal oscillator with the vibration isolation system is measured next.

V. Experimental Results

In the random vibration environment, the phase noise of crystal oscillator without isolator is shown in Fig.4 and Table I; the phase noise of crystal oscillator with the vibration isolation system is shown in Fig.5 and Table I.

TABLE I. THE RESULT OF PHASE NOISE IN THE RANDOM VIBRATION ENVIRONMENT

12.8MHz AT-cut Crystal Oscillator	Phase noise from offset frequency (dBc)			
	10Hz	*100Hz*	*1KHz*	*10KHz*
Without Isolator	-82	-100	-102	-122
With Isolator	-87	-103	-120	-136

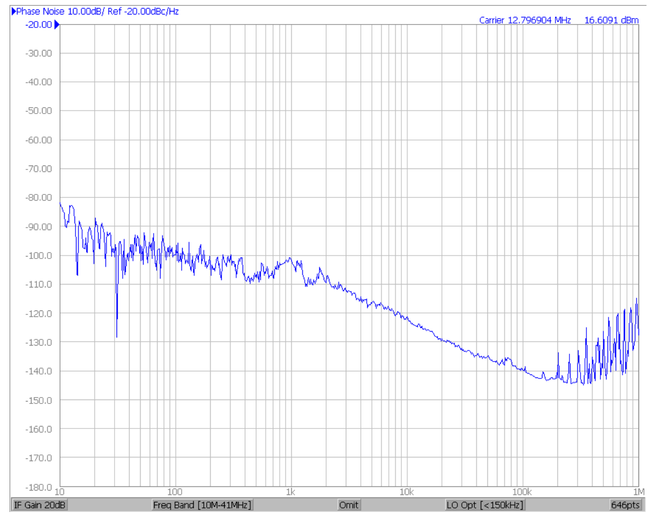

Figure 4. The phase noise of crystal oscillator without isolator in the random vibration environment

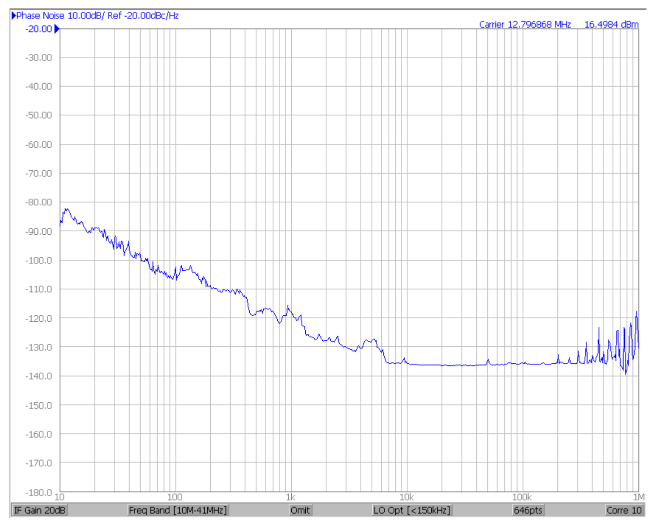

Figure 5. The phase noise of crystal oscillator with the vibration isolation system in the random vibration environment

The experimental result shows that the vibration isolation system reduced the phase noise induced by vibration. Compare the phase noise of the crystal oscillator with and without isolator, we can find that at the offset frequency between 100Hz and 10KHz, the decrease of phase noise caused by vibration isolation system of significant, but the decrease of phase noise is not so significant at the offset frequency lower than 100Hz. It is possible to be improved by introducing nonlinear elements into the parameters of system.

VI. Conclusions

According to the above analysis, simulation and experimental testing, it is demonstrated that two-stage passive vibration isolation system can reduce the phase noise of crystal oscillator induced by vibration effectively, especially in a high-frequency vibration environment.

Furthermore, it is possible to improve the performance of this vibration isolation system by improving the parameters of the systems, such as introducing some nonlinear elements into parameters, and this is presently under study.

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