Vibration Sensitivity of Microwave Components*

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Abstract — **Vibration sensitivity is an important specification for oscillators on mobile systems, unmanned aerial vehicles (UAVs) etc. These systems must provide superior performance when subject to severe environmental conditions. Electronic oscillators often can provide sufficiently low intrinsic phase modulation (PM) noise to satisfy particular system requirements when in a quiet environment. However, mechanical vibration and acceleration can introduce mechanical deformations that degrade the oscillator's otherwise low PM noise. This degrades the performance of an electronic system that depends on this oscillator's low phase noise. Not only an oscillator, but most microwave components, such as microwave cables, circulators, and amplifiers are sensitive to vibration to some extent. Therefore, it is very important to select vibration-tolerant components in order to build a system with less vibration sensitivity. We study the performance of different microwave cables (flexible, semi-rigid as well as rigid) under vibration for different vibration profiles. Some good cables provide a vibration-sensitivity noise floor that provides sensitivity of 10^{-11}-10^{-12} per g for an oscillator under test. We also verify the reproducibility of each measurement after disassembly and reassembly. We study the vibration sensitivity of a SiGe amplifier-based surface transverse wave (STW) oscillator and an air-dielectric cavity resonator oscillator (ACRO) and compare their performances with a commercially available dielectric resonator oscillator (DRO). We also describe passive and active vibration cancellation schemes to reduce vibration induced noise in oscillators.**

I. INTRODUCTION

High precision oscillators have significant applications in modern communication, navigation and radar systems particularly in unmanned aerial vehicles. A principle problem in the use of precision oscillators is the random modulation noise on the oscillating signal due to acceleration [1-5]. The acceleration can be in the form of steady state acceleration, vibration, shock, and acoustic noise. The moderately close-in phase modulated (PM) noise performance of oscillators and other components depend on the vibration and acceleration environment. This is because typical mechanical vibrations, hence, accelerations, predominantly occur in and affect a frequency range similar to an important offset frequency (f) range that characterizes PM noise, namely, $1 < f < 2{,}000$ Hz. There are other environmental effects that can degrade PM noise [6-7]. The practical noise limitation of low noise oscillators is set by its vibration sensitivity. Vibration sensitivity of oscillators is traditionally characterized by acceleration or g-sensitivity and typically produces frequency shifts in oscillators on the order of 10^{-9} to 10^{-10} per g, primarily because of physical deformations in the oscillator. "g" is the acceleration of gravity near the earth's surface, which is approximately 9.8 m/sec^2.

This paper is intended to introduce the subject of vibration-induced PM noise by discussing the method of characterizing vibration sensitivity and reporting such characterization on a sample of devices operating at microwave frequencies. To a first approximation, vibration-induced noise can be suppressed by physical means and further by electronic means if a suitably low-cost way of measuring and correcting the vibration-induced noise from an oscillator is built in [1, 8-9]. A few schemes for reducing vibration induced noise are also proposed.

In this paper we report the vibration sensitivity of different components, mainly oscillators at microwave frequencies. Sections II and III, respectively, describe the characterization of vibration sensitivity and the experimental procedure to measure vibration sensitivity of components. Experimental results are presented in Section IV. A few passive and active vibration cancellation techniques for improving vibration sensitivity in oscillators are proposed in Section V. Finally, the results of the paper are summarized in Section VI.

II. CHARACTERIZING VIBRATION SENSITIVITY

If the vibration frequency from mechanical shock or other external processes is f_v, vibration-induced phase fluctuations cause carrier-frequency fluctuations characterized as $\Delta f/f_0$ at f_v, where f_0 is the carrier frequency. Spurious sidebands, a highly undesirable type of noise in many applications, will appear at $f_0 \pm f_v$. Fig. 1 shows the PM noise of one test oscillator that is subjected to 100 Hz vibration along one axis. Note that the intrinsic random electronic noise is degraded by additional noise due to this vibration, and the resulting upper and lower sidebands at f_v = 100 Hz produce the increase in PM noise that is indicated.

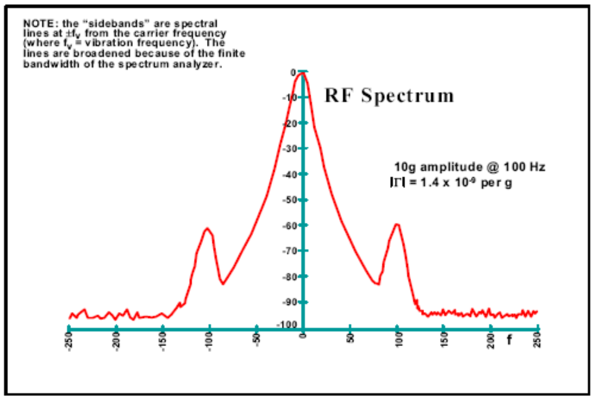

Figure 1. Power spectrum of an oscillator that is subjected to 10 g vibration at f_v = 100 Hz. Figure is shown courtesy of John Vig [2].

Low acceleration or g-sensitivity at one frequency such as 100 Hz does not necessarily mean that phase noise due to acoustic and structure-borne vibration is suppressed. While vibration-induced noise modulation on an oscillator may be proportional to overall g-sensitivity, the proportionality as a function of f_v can be complicated in the range of audio frequencies of concern here (from a few Hertz to 2 kHz). Resonator deformations that affect the resonator's center frequency depend on issues of mounting, elastic properties of materials, acoustic resonances, sound and vibration isolation, orientation, etc. Therefore, suppression of only "dc" g-sensitivity has limitations and is insufficient to solve the larger problem of "ac" vibration sensitivity. Therefore, g-sensitivity is characterized more fully as a function of f_v, as discussed next.

Acceleration or vibration sensitivity of oscillators is explained in detail in [1]. When an oscillator is subjected to acceleration, its resonant frequency shifts. The change in frequency Δf is proportional to magnitude and dependent on the direction of acceleration, and is given by

$$\frac{\Delta f}{f_0} = \vec{\Gamma} \bullet \vec{a}\,, \qquad (1)$$

where f_0 is the frequency of the oscillator with no acceleration, $\vec{a}$ is the applied acceleration, and $\vec{\Gamma}$ is the vibration sensitivity vector. In this paper the magnitude of acceleration is expressed in units of g. For a low modulation index, the vibration induced single sideband phase noise, $L(f_v)$ is related to vibration sensitivity as follows [1]:

$$L(f_v) = 20\log\left(\frac{\vec{\Gamma} \bullet \vec{a}}{2 f_v} f_0\right). \qquad (2)$$

In most cases, vibration experienced by an oscillator is random instead of sinusoidal. Under random vibration the power is randomly distributed over a range of frequencies, phases and amplitudes, and the acceleration is represented by its power spectral density (PSD). For a sinusoidal vibration, $|\vec{a}|$ is the 0-to-peak g level, and for random vibration $|\vec{a}| = \sqrt{2PSD}$, and its unit is $g_{peak}/\sqrt{Hz}$. Thus, the vibration sensitivity in any axis i (i = x, y and z) can be determined from phase noise by

$$\Gamma_i = \frac{2 f_v}{a_i f_0} 10^{\left(\frac{L(f_v)}{20}\right)}. \qquad (3)$$

III. Experiment

One goal of this paper is to measure the vibration sensitivity of different microwave components. In order to accurately measure the vibration sensitivity of a device under test (DUT), it is very important to know the vibration sensitivity noise floor first. Compared to everything else, microwave-cable flexure generally sets the noise floor. Fig. 2 shows the block diagram of a single channel PM noise measurement system used to measure the residual noise of cables under vibration. The output power of a reference oscillator is split into two parts. One part is used to drive the DUT, which in this case is a 12 foot cable under vibration, and the other part is connected to a delay line. The delay is chosen so that the delay introduced in one path is equal to the delay in the other path. A phase shifter is used to set true phase quadrature between two inputs to a mixer, which acts as a phase detector (PD).

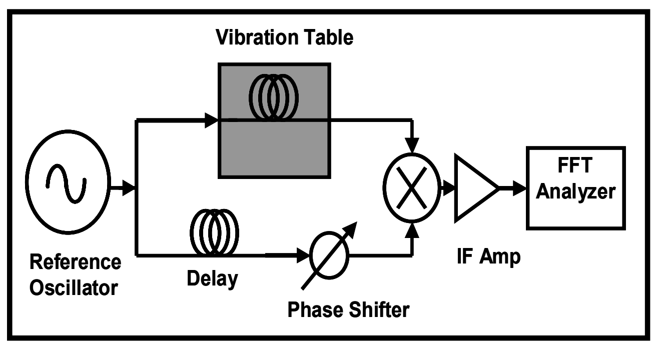

Figure 2. Experimental setup for measuring vibration sensitivity of cables.

The output of the detector is then amplified and fed to a fast Fourier transform (FFT) spectrum analyzer. Since the delays in the two signal paths are equal, this technique cancels the noise introduced by the reference oscillator. At the output, only the noise of the vibrating cable, phase detector and IF amplifier appear. A low noise PD and IF amplifier are chosen for this experiment, and their noise contributions are much lower than vibration-induced cable noise. Three different types of cables, viz. flexible, semi-rigid and rigid cables, were tested under sinusoidal and random vibration. A sinusoidal vibration of magnitude 0.5 g_{peak} and random vibration profile of acceleration PSD 0.5 mg_{rms}^2/Hz for offset frequencies 10 Hz to 1200 Hz were used. Fig. 3(a) shows the PM noise floor of the measurement system with and without vibration using a semi-rigid cable. The vibration sensitivity is calculated using equation (3) for both sinusoidal as well as random vibration, and they are in close agreement. A comparison of vibration sensitivity of three cables is shown in Fig. 3(b). These cables set a noise floor that provides a sensitivity of 10^{-11} to 10^{-12} per g for an oscillator under test.

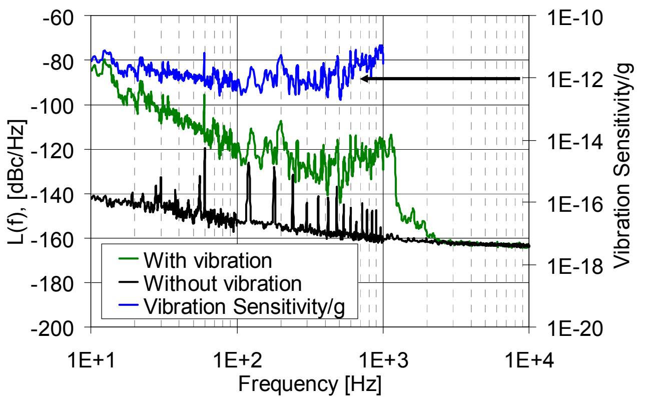

Figure 3(a). PM noise floor of the measurement system measured with and without vibration using a semi-rigid cable. A random vibration profile of acceleration PSD 0.5 mg_{rms}^2/Hz for offset frequencies 10 Hz to 1200 Hz was used.

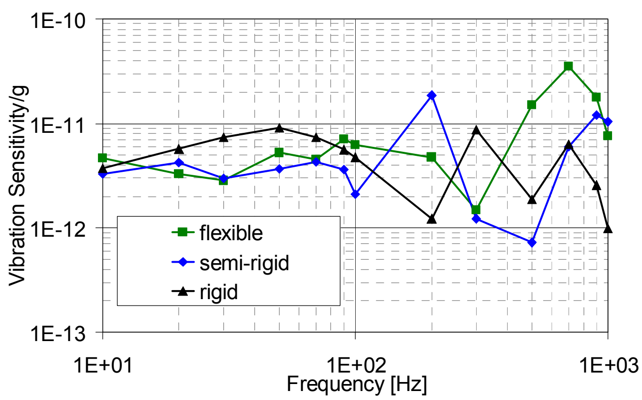

Figure 3(b). Vibration sensitivity noise floor of the measurement system due to vibrating cables.

After determining the noise floor due to cable vibration, the sensitivity of three different types of oscillators, viz. a DRO, a silicon germanium (SiGe) amplifier-based surface transverse wave (STW) oscillator, and a TE_{023} mode air-dielectric ceramic cavity resonator oscillator (ACCRO), were measured [10]. These oscillators are shown in Fig. 4. Fig. 5 shows the setup used to measure vibration sensitivity of different oscillators. It consists of a direct digital phase noise measurement system (DPNMS) to measure the PM noise between a low noise reference signal and the DUT [11]. The advantage of the DPNMS vs. analog system is that there is no need for a phase locked loop (PLL), and as a result PM noise of a noisy source as well as a quiet source can be measured accurately for offset frequencies very close to the carrier.

The oscillator under test is mounted on a vibration table with the output going to one input of a double balanced mixer. This output is then mixed with a very low PM noise source to generate a beat frequency anywhere between 1 MHz to 30 MHz. This restriction is necessary because the DPNMS does not work outside this frequency range. The beat frequency is then compared with the output of a 10 MHz quartz crystal oscillator.

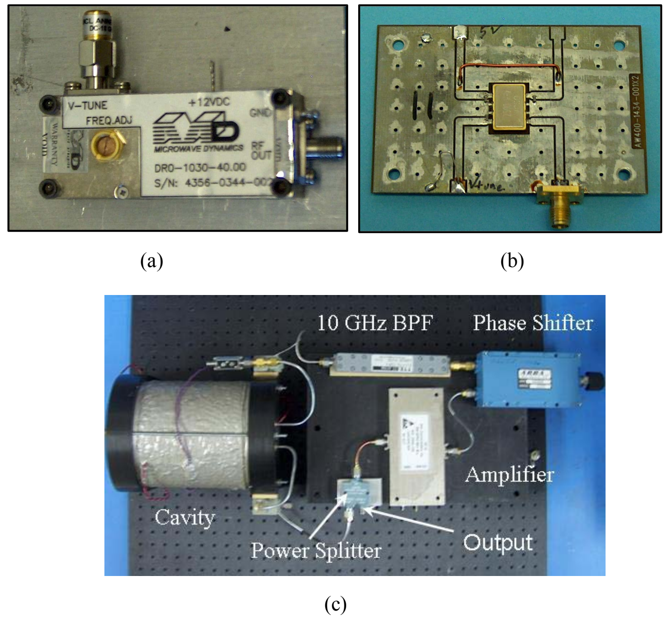

Figure 4. Pictures of three different types of oscillators used for vibration test. (a) DRO, (b) STW oscillator, (c) ACCRO.

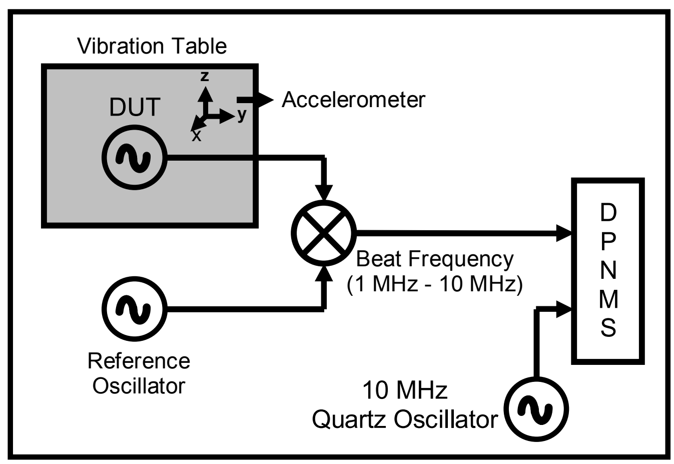

Figure 5. Experimental setup for measuring vibration sensitivity of oscillators.

The equipment needed to vibrate a device consists of a vibration table or "shaker," a table driver or power amplifier, the main power isolator and transformer, and a vibration controller with an associated accelerometer mounted on the shaker. A separate computer is used to control the amplifier, which in turn controls the vibration of the table. The controller card is part of a control loop that relies on an accelerometer mounted to the vibration table. This accelerometer provides the feedback data that the computer uses to calculate the ideal output signal and amplitude for the amplifier to drive the table to the specified software parameters set by the operator.

The table has the capability to vibrate either in a random vibration pattern or in various sine patterns, including dwell and sweep. For this test, sine dwelling and random vibration testing were chosen. For each axis of the oscillator, sine dwelling was used for verification, followed by random vibration. The frequencies chosen for a sine dwell were 10, 20, 30, 50, 70, 90, 100, 200, 300, 500, 700, 900, 1000, and 2000 Hz. These frequencies showed the desired results. Then, a random vibration pattern was used, vibrating at frequencies between 10 and 2000 Hz.

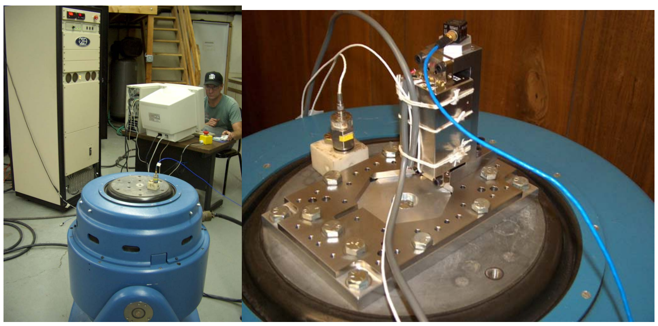

Figure 6. Pictured on the left is the vibration table (shaker); the amplifier for driving the shaker (the vertical rack-mount system); and the controller, signal generator, and data-acquisition system. On the right is the device under test (DUT) mounted on the vibration table.

IV. Measurement Results

At first the PM noise of three oscillators was measured with no vibration; the PM noise plots are shown in Fig. 7.

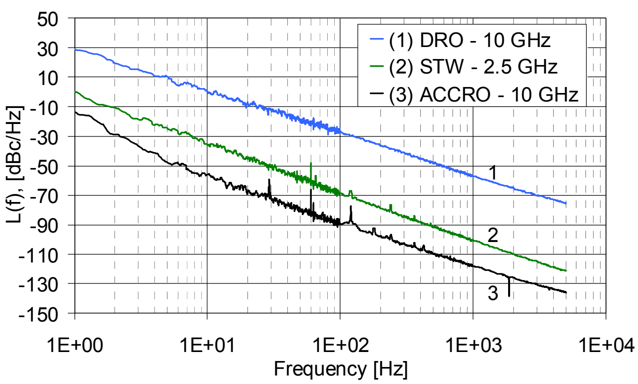

Figure 7. PM noise of three different oscillators with no vibration.

Then a commercial DRO at 10 GHz was subjected to a random white-noise vibration profile with acceleration PSD of approximately 0.5 mg_{rms}^2/Hz along three axes independently. The degradation in PM noise due to vibration in the z-axis is shown in Fig. 8(a). The effect of random vibration in the x and y axes was not noticeable because the PM noise of the DRO by itself is higher than the random noise.

In order to measure the vibration sensitivity in all three axes, different sinusoidal dwell frequencies were used; the results are shown in Fig. 8(b). This particular DRO is more sensitive to vibration along the z-axis than along the other two axes. The z-axis vibration sensitivity was also calculated using a random vibration profile and is nearly equal to that obtained with sinusoidal dwell frequencies.

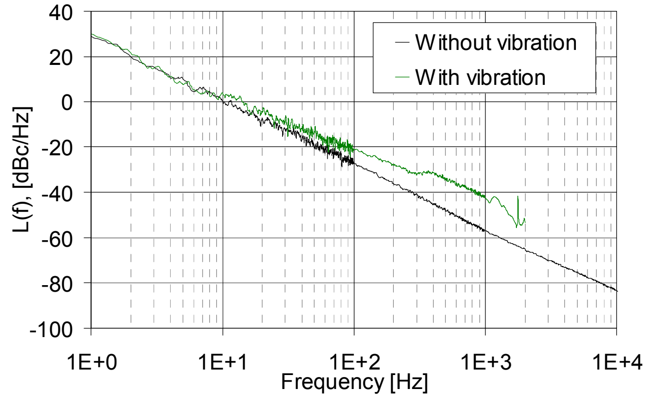

Figure 8(a). PM noise of the DRO with and without vibration along the z-axis. A random vibration profile of acceleration PSD 0.5 mg_{rms}^2/Hz for offset frequencies 10 Hz to 1500 Hz was used.

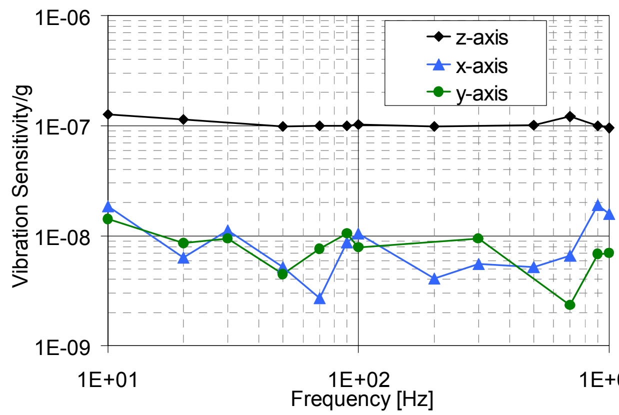

Figure 8 (b):. Vibration sensitivity of a DRO. a = 0.5 g_{peak} was used for sinusoidal dwell frequencies.

Fig. 9 shows the z-axis vibration sensitivity of three oscillators. The vibration sensitivity of the STW is two orders of magnitude lower than that of the DRO.

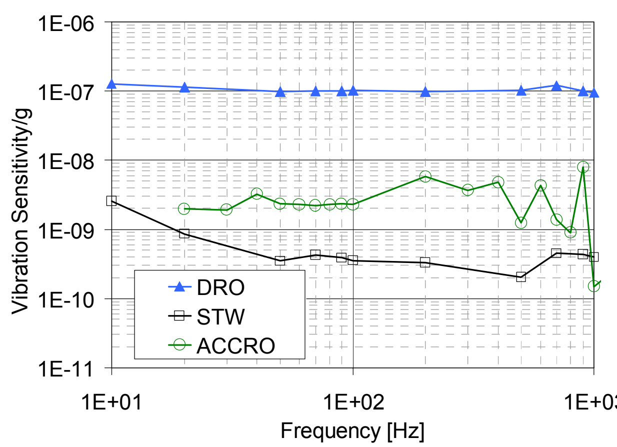

Figure 9. z-axis vibration sensitivity of different oscillators. a = 0.5 g_{peak}.

The vibration sensitivity of a feed-forward amplifier (FFA) at 10 MHz and an array amplifier at 10 GHz were also measured [12]. The vibration sensitivity of these amplifiers is very low, lower than the vibration sensitivity noise floor provided by the cables. As a result, an accurate measurement was not possible. From Fig. 10 it can be concluded that vibration sensitivity/g of the FFA and array amplifier is no greater than 10^{-11}.

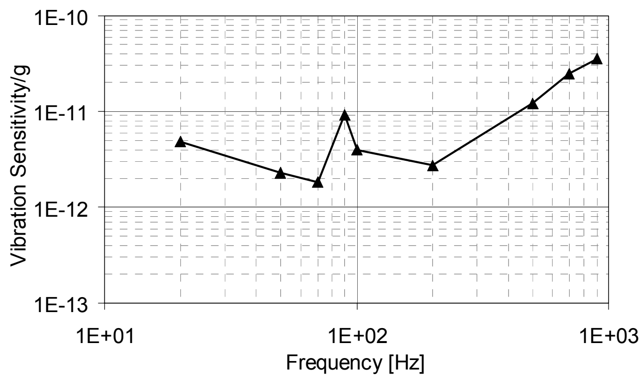

Figure 10. Vibration sensitivity of feed-forward amplifier and array amplifiers measured for a = 0.5 g_{peak}. Vibration sensitivity per g of these amplifiers is no greater than 10^{-11}.

V. VIBRATION REDUCTION TECHNIQUES

In this section, a few methods of reducing vibration-induced noise from vibration-sensitive components are discussed. The most common approach for reducing vibration-induced phase noise is to select low vibration-sensitive materials. We built two air-dielectric cavity oscillators, one cavity made of aluminum and another one made of ceramic. Two cavities were chosen so that they have almost identical loaded Q's of 22,000 (TE_{023} mode) and insertion loss of 6 dB. All other components of two oscillators were identical.

We tested these two oscillators for different sinusoidal dwell frequencies and found that the vibration sensitivity of the ceramic cavity oscillator is almost six times lower than that of the aluminum cavity oscillator, as shown in Fig. 11. This result was expected because ceramic is more stiff than aluminum.

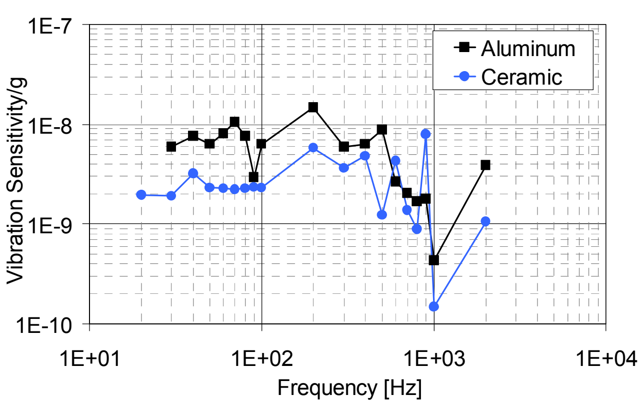

Figure 11. Comparison of vibration sensitivity of aluminum and ceramic air-dielectric cavity resonator oscillators.

It is worth also noting a few tests of passive mechanical dampers and isolators on different test oscillators. The vibration impact on any system depends on structure-borne vibrations and perturbations on that system, and passive dampers act to terminate resonances. We used these dampers for the DRO and STW oscillators and noticed significant improvement in the vibration sensitivity, as shown in Fig. 12.

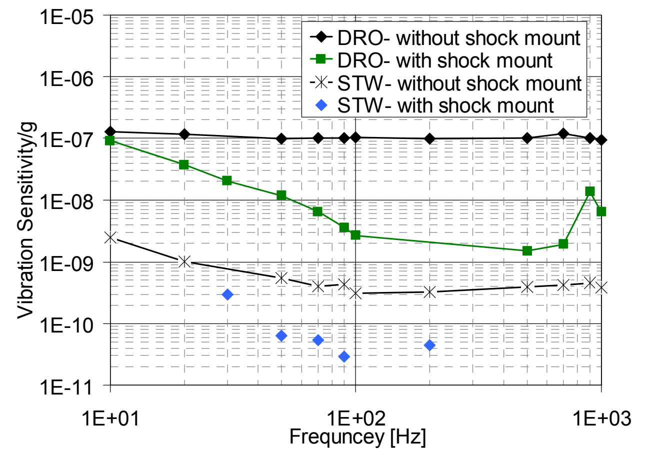

Figure 12. Improvement in vibration sensitivity using shock mount.

Finally, an active vibration cancellation technique is proposed to reduce the vibration sensitivity in oscillators. Fig. 13(a) shows the block diagram of the proposed technique with the ACCRO as the DUT.

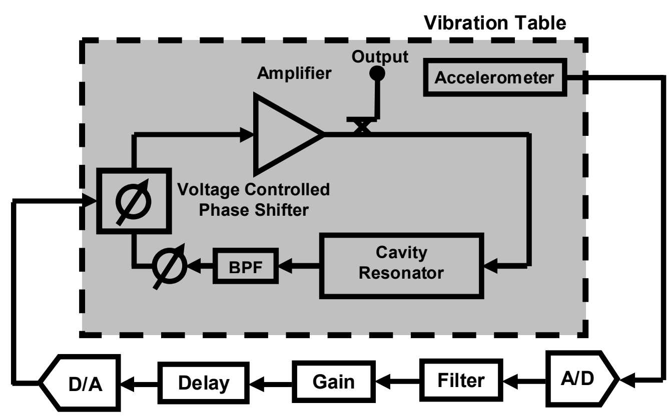

Figure 13 (a). Block diagram of experiment to suppress vibration-induced PM noise in ACCRO.

A voltage variable phase shifter is introduced in the ACCRO, and a vibration sensor (z-axis accelerometer) is also attached to the oscillator. When the oscillator is under vibration, the sensor generates an estimated signal proportional to vibration. This signal, after proper amplification and phase shift, is used to modulate the voltage control port of the phase shifter. If the modulated signal and the vibrating signals are of equal amplitude and opposite phase, the vibration-induced phase perturbations cancel out due to this feed-forward technique. The proposed technique can be used to cancel random white noise vibration as well as unwanted vibration frequency from mechanical shock or other external processes. We used this noise cancellation technique for a few spot frequencies using sinusoidal dwelling. By adjusting proper gain and delay, it is possible to improve the vibration sensitivity of the oscillator. Fig. 13 (b) shows the improvement in vibration sensitivity of the ACCRO at few spot frequencies for a fixed gain and delay in the cancellation circuit.

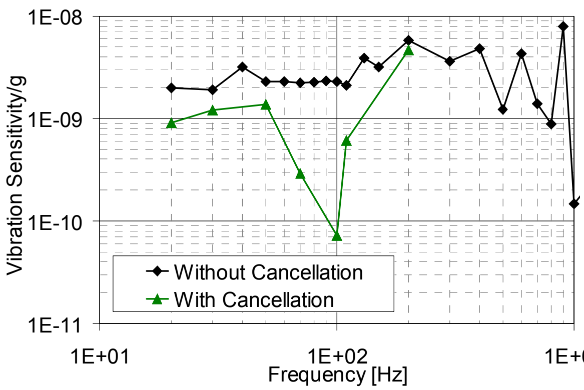

Figure 13 (b). Plot of vibration sensitivity of ACCRO with and without vibration cancellation.

VI. CONCLUSION

Vibrations are undesirable to precision, low-noise oscillators. In this paper we briefly discuss the vibration sensitivity and it relation with PM noise of an oscillator. We describe the vibration sensitivity measurement techniques and present results of vibration sensitivity of different oscillators. We verify the reproducibility of each measurement after disassembly and reassembly. We also propos different passive and active techniques to suppress or cancel vibration induced noise in these oscillators.

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