IEEE TRANSACTIONS ON ULTRASONICS, FERROELECTRICS, AND FREQUENCY CONTROL, VOL. 63, NO. 3, MARCH 2016

Oscillator PM Noise Reduction From Correlated AM Noise

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***Abstract*—We demonstrate a novel technique for reducing the phase modulation (PM) noise of an oscillator in a steady-state condition as well as under vibration. It utilizes correlation between PM noise and amplitude modulation (AM) noise that can originate from the oscillator's loop components. A control voltage proportional to the correlated AM noise is generated and utilized in a feedforward architecture to correct for the steady state as well as the vibration-induced PM noise. An improvement of almost 10–15 dB in PM noise is observed over one decade of offset frequencies for a 635-MHz quartz-MEMS oscillator. This corresponds to more than a factor of five reductions in vibration sensitivity.**

***Index Terms*—Amplitude modulation (AM) noise, correlation, oscillator, phase modulation (PM) noise, vibration sensitivity.**

I. INTRODUCTION

LOW PHASE noise is a primary performance requirement for advanced communications, GPS applications, high-speed computing, and defense systems such as surveillance, radar, remote sensing, and military GPS [1]–[5]. As phase stability requirements become ever more stringent for these applications, more focus is needed on designing low-phase noise oscillators. However, the great majority of useful applications of precision oscillators and timing systems occur where environmental conditions can substantially degrade phase noise and compromise system performance. Environmental parameters such as temperature and humidity can often be controlled easily. But vibration and acceleration can be major sources of phase noise that cannot be easily controlled—for example, in flying aircraft, traveling motor vehicles, or even stationary systems subject to normal environmental vibrations.

If the phase modulation (PM) noise of an oscillator can be measured in real time, it can be corrected. A direct PM noise measurement is complicated, cumbersome, and expensive because it requires a second, superior reference. There are several known feedback and feedforward noise reduction techniques [6] that have been successfully implemented to reduce the phase noise of an oscillator in steady-state conditions. In this paper, we present a new technique that utilizes indirect measurement of PM noise via correlated amplitude modulation (AM) noise. This scheme uses feedforward electronic phase correction for the mitigation of vibration-induced as well as steady-state phase fluctuations in an oscillator. In contrast to direct PM noise measurement, this technique does not require a second superior reference oscillator. It uses an AM detector which has a significant advantage as a simpler, smaller, and less expensive device. We demonstrate that if there is a strong correlation between PM and AM noises, then AM noise can be used to compensate for the PM noise of an oscillator. Such correlation between PM and AM noises can originate in the loop amplifier through up-converted current noise [7]–[9], due to asymmetry in the resonator, nonlinear effects [10]–[12], or through vibration-induced noise in the resonator and other loop components.

This paper is organized as follows. Section II provides simulation and experimental results to prove that if the PM and AM noises of an oscillator are correlated, then the PM noise can be reduced by use of the correlated AM noise. We demonstrate that an improvement of more than 20 dB is possible if the correlation between PM and AM noises is more than 90%. We also implement this technique in a 635-MHz quartz-MEMS oscillator to improve the phase noise performance. This particular oscillator is chosen because the quartz-MEMS resonator [13] used in the oscillator exhibits a strong conversion of AM to PM noise under certain operating conditions. In Section III, we discuss the construction of a quartz-MEMS oscillator and provide the results of its PM noise, AM noise, and the correlation between the two noise types. The active PM–AM noise correction scheme for the oscillator operating in steady state and under vibration is discussed, respectively, in Sections IV and V. Finally, conclusions are presented in Section VI.

II. PROOF OF PRINCIPLE

For a proof of concept that correlated AM noise can be utilized to reduce the PM noise in an oscillator, we first set up a simple experiment as shown in Fig. 1. A 635-MHz carrier signal from a commercial signal generator represented as device under test (DUT) is simultaneously FM and AM modulated with a common white-noise source. This produces correlated PM (f^{-2} slope) and AM (f^{0} slope) noises. An I/Q demodulator is implemented to measure the single-sided PM noise, AM noise, and the cross-power spectral density (CPSD) between them. These quantities are, respectively, defined as

$$S_{\varphi}(f) = \frac{2}{T}\langle \Phi(f)\Phi^{*}(f)\rangle_{m}, \quad \varphi(t) = \tan^{-1}\left(\frac{Q(t)}{I(t)}\right) \tag{1}$$

$$S_{\alpha}(f) = \frac{2}{T}\langle \mathrm{A}(f)\mathrm{A}^{*}(f)\rangle_{m},$$

$$\alpha(t) = \frac{\sqrt{I^2(t)+Q^2(t)} - \left\langle \sqrt{I^2(t)+Q^2(t)} \right\rangle}{\left\langle \sqrt{I^2(t)+Q^2(t)} \right\rangle} \tag{2}$$

Manuscript received June 23, 2015; accepted January 4, 2016. Date of publication January 25, 2016; date of current version March 11, 2016.

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Digital Object Identifier 10.1109/TUFFC.2016.2521614

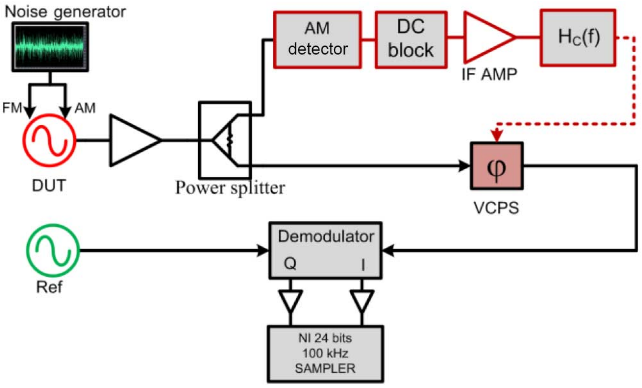


Fig. 1. Experimental setup for correcting PM noise using correlation between PM and AM noises in an oscillator. DUT–device under test; IF AMP-intermediate frequency amplifier; VCPS-voltage-controlled phase shifter.

and

$$S_{\varphi\alpha}(f) = \frac{2}{T}\langle \Phi(f)\mathrm{A}^*(f)\rangle_m . \quad (3)$$

Here, $\varphi(t)$ and $\alpha(t)$ are the instantaneous phase and amplitude fluctuations, $\Phi(f)$ and $\mathrm{A}(f)$ are the respective Fourier transforms, T is the measurement time normalizing the PSD to 1 Hz, "*" indicates the complex conjugate, and $\langle\ \rangle_m$ denotes an ensemble of m averages. The results in decibel (dB) for PM, AM, and CPSD are displayed in Fig. 2(a).

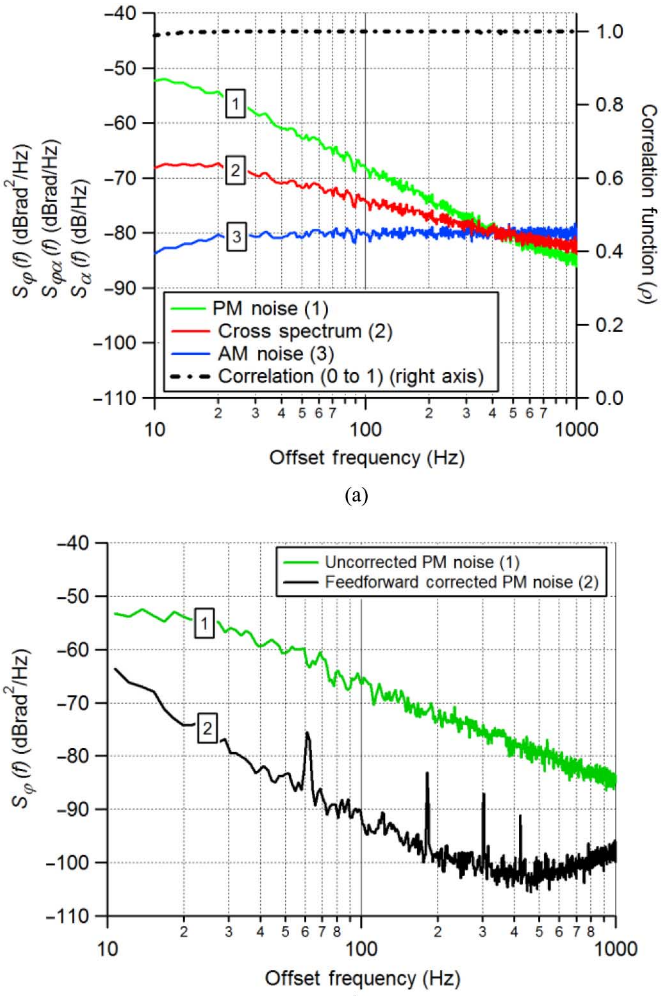
The degree of correlation between PM and AM noises can be described by a correlation function, ρ [14]

$$\rho = \frac{S_{\varphi\alpha}}{\sqrt{S_\varphi S_\alpha}} \quad (4)$$

where $\sqrt{S_\varphi S_\alpha}$ is the geometric mean of S_φ and S_α. The values of ρ range from 0 to 1, and $\rho = 1$ represents 100% correlation. In our experiment, the cross-spectrum is exactly the expected geometric mean between 10- and 1000-Hz offset frequencies indicating 100% correlation. A high level of correlation is due to the fact that PM and AM noises both originate from the same white-noise source. As shown in Fig. 2(a), the slope between PM and AM noises is f^{-2}, so if we generate a control signal utilizing the AM noise that is of same magnitude, the same noise slope, and opposite phase as the PM noise, then this control signal can be used in a feedforward approach to reduce the PM noise. To achieve the desired signal, a portion of the modulated carrier at 635 MHz is AM detected as shown in Fig. 1. Two transfer functions are measured and used to calculate the required control function. First, $H_{\mathrm{AM-PM}}(f)$ is determined from the ratio of the measured AM noise at the output of the AM detector to the PM noise of the I-Q demodulator. The second transfer function $H_{\mathrm{VCPS}}(f)$ is measured between the input of the voltage-controlled phase shifter (VCPS) and the PM output of the demodulator. Finally, the control transfer function $H_C(f)$ is obtained from

$$H_C(f) = -\frac{H_{\mathrm{AM-PM}}(f)}{H_{\mathrm{VCPS}}(f)}. \quad (5)$$

The detected AM signal is then filtered with the transfer function $H_C(f)$ and applied to the control port of the VCPS. The phase noise of the 635-MHz signal is measured with and without the control signal as shown in Fig. 2(b). We see an improvement greater than 20 dB over two decades of offset frequencies. Here, we clearly demonstrate that if an oscillator exhibits a strong correlation between PM and AM noises, then the AM noise can be used to compensate the PM noise.



(a)

(b)

Fig. 2. (a) Plot of the PM noise, AM noise, and the cross-spectrum of the DUT at 635 MHz (left axis). The plot shows 100% correlation ($\rho = 1$) as shown on the right axis. (b) Plot of PM noise: 1) no feedforward control; 2) with feedforward control.

Simulations for the reduction in phase noise due to PM–AM correlation were produced in labVIEW with the block diagram shown in Fig. 1. The simulation results at a 100-Hz offset frequency for different correlation functions are shown in Fig. 3.

III. PM–AM CORRELATION IN A QUARTZ-MEMS OSCILLATOR

We implemented the technique of PM noise reduction from the correlated AM noise in a 635-MHz quartz-MEMS oscillator. This oscillator is chosen because the quartz-MEMS resonator exhibited a strong conversion of AM to PM noise [13], [15], [16]. When an amplitude modulated signal is applied to

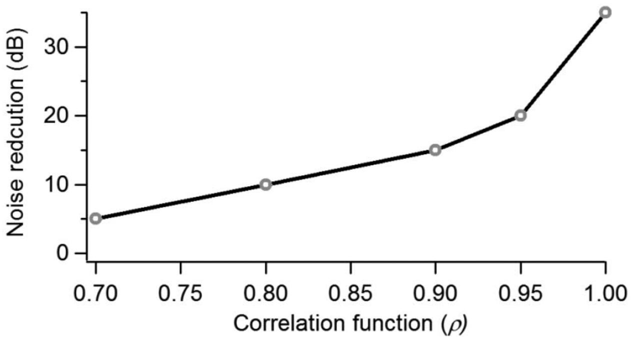


Fig. 3. Simulation result showing the amount of noise reduction as a function of correlation function.

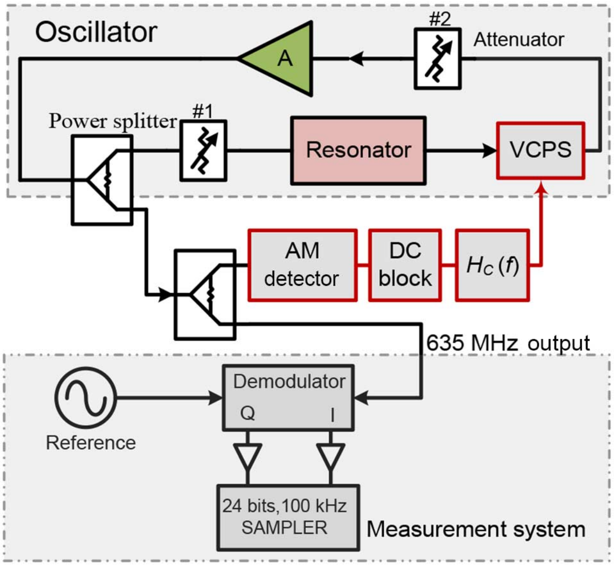


Fig. 4. Block diagram of the quartz-MEMS oscillator at 635 MHz with control circuit.

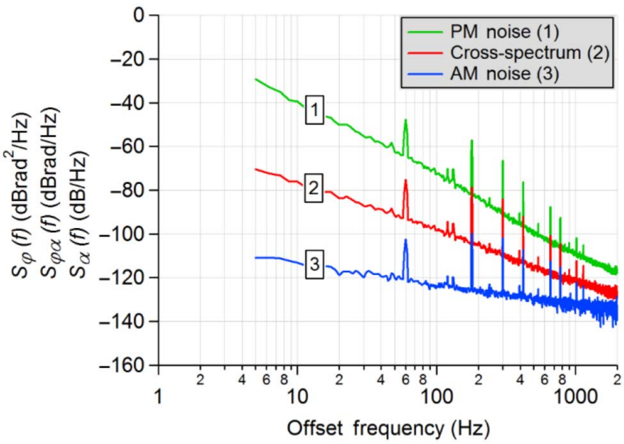


Fig. 5. Plot of PM noise, AM noise, and the cross-spectrum for the quartz-MEMS oscillator at 635.17 MHz.

this resonator, it produces unequal upper and lower sidebands [12]. The asymmetry of sidebands confirms that a portion of the AM noise is converted to phase noise [17]. This asymmetry increases with increasing input power to the resonator. For $+2.5\ \mathrm{dBm}$ input power, an AM tone at 100 Hz produces an almost equal level of PM sidebands. The block diagram of the oscillator designed with this resonator is shown in Fig. 4, where we introduce the VCPS inside the loop. The input and output power of the resonator are adjusted using variable attenuators 1 and 2. The loaded quality factor (Q_L) of the resonator is approximately 5200, and the amplifier "A" in series with the resonator has gain, noise figure, and 1 dB compression power of 20 dB, 4 dB, and 18 dBm, respectively. The phase noise of the amplifier is $-132\ \mathrm{dBrad}^2/\mathrm{Hz}$, and the flicker noise floor of the AM detector is approximately $-130\ \mathrm{dB/Hz}$ at 1-Hz offset.

The PM noise of the oscillator was measured for different input powers. We made the following observations for this quartz-MEMS oscillator.

1) As the input power of the resonator increases, the resonant frequency of the oscillator moves to a higher frequency.
2) Whenever the gain of the sustaining amplifier only marginally exceeds the loss in the oscillator loop, most of the saturation occurs in the resonator rather than the amplifier; under this operating condition, we observe strong correlation between PM and AM noises.
3) As the input power of the resonator increases and the amplifier goes deeper into saturation, the correlation between PM and AM noises decreases.
4) If the power to the input of the resonator is increased $(> 5\ \mathrm{dBm})$, then both resonator and amplifier are at or above 1-dB compression; a degradation in the PM noise of the oscillator is observed; and we again see strong correlation between AM and PM noises.

Operating condition (2) was addressed for this study. Such a condition occurs when the input powers to the resonator and amplifier are approximately $+0.5$ and -11 dBm, respectively. The AM, PM, and CPSD measurement of this oscillator at 635.17 MHz are shown in Fig. 5. It is interesting to see that close-to-carrier CPSD is exactly the expected geometric mean, even for very widely differing levels of PM and AM noises, and this means that substantially complete correlation exists for this quartz-MEMS oscillator.

IV. ACTIVE PM–AM NOISE CORRECTION IN QUARTZ-MEMS OSCILLATOR

Next, the phase noise of the oscillator is measured with the control circuit (red section of Fig. 4) enabled. There is a slight difference in the control circuit configuration; the VCPS is inside the oscillator loop unlike Fig. 1 where the correction is occurring outside the loop. Moving the VCPS inside the oscillator loop has the advantage of reducing the order of the control transfer function $H_C(f)$ that is required. The integration of the AM noise that is required to match the PM noise slope can be achieved automatically via the Leeson's effect [18] by applying the feedforward signal to the VCPS inside the oscillator loop. We see almost 10-dB improvement from 2- to 100-Hz offset frequencies by implementing the control circuit. We also noticed that the correlation between PM and AM noises decreases when we introduce the control circuit as shown in the inset of Fig. 6. This is because the control circuit is removing the correlated portion of the PM noise.

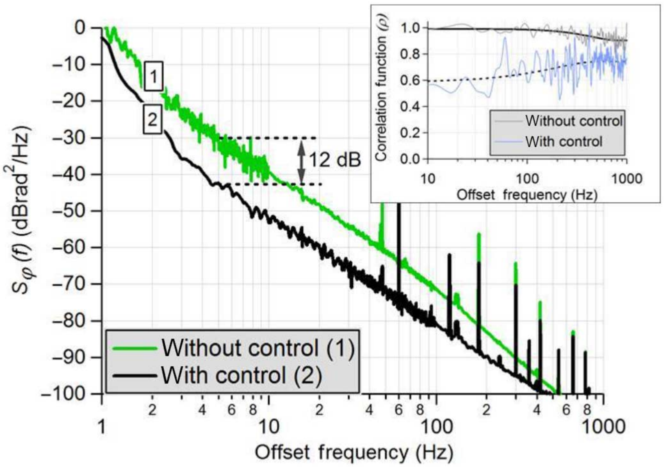


Fig. 6. Experimental results of PM noise of the oscillator with and without feedforward correction (resonator input power $= 0.5$ dBm). The amount of improvement at higher offset frequencies is less due to the deviation from f^{-2} slope between PM and AM noises. Inset: Correlation between AM and PM noises of the oscillator with and without feedforward correction.

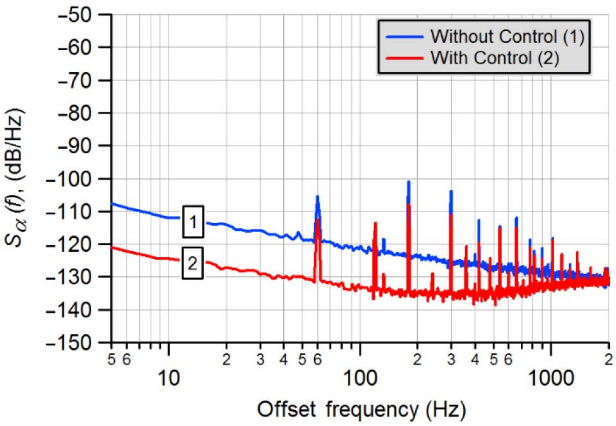


Fig. 7. Experimental results of AM noise of the quartz-MEMS oscillator at 635 MHz with and without feedforward correction.

In addition, we also compared the AM noise of the oscillator with and without control and observed more than 10-dB improvement in AM noise when the control circuit is turned ON (as shown in Fig. 7). This may explain why the improvement is limited to only 10 dB. To verify whether there is undesired AM modulation generated by the VCPS, we applied a constant amplitude tone to the control port of the VCPS without affecting the oscillator closed-loop configuration and then measured the PM, AM, and CPSD response. As shown in Fig. 8, we see the AM response is more than 30 dB below the PM for $f < 500$ Hz, indicating negligible AM leakage and that the reduction in AM noise with the control circuit is in fact due to the PM control.

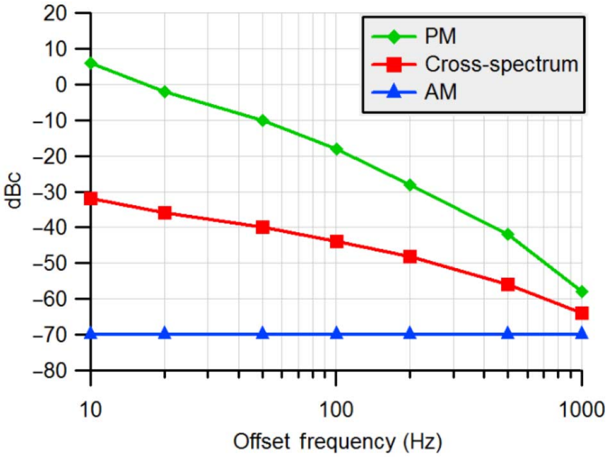


Fig. 8. Plot of the residual AM noise of the VCPS.

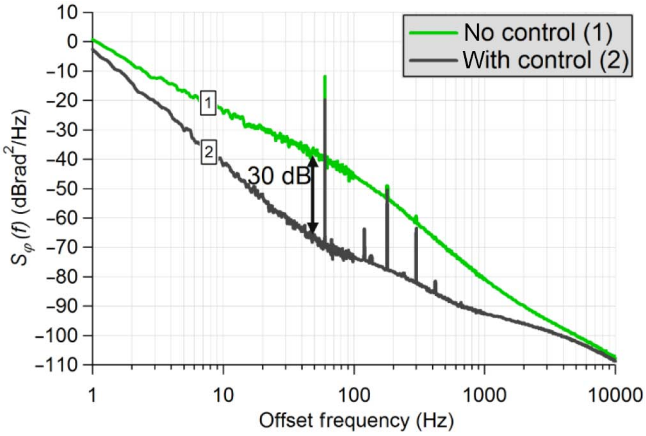


Fig. 9. Experimental results of PM noise of the oscillator with and without feedforward correction when artifically high correlated PM–AM noise was generated by introducing noise to the loop amplifier bias current.

We have so far described improvement in PM noise due to correlated PM–AM noise originating mainly from the resonator; however, our scheme can also improve the phase noise of an oscillator if this correlation originates from the loop amplifier or other loop components simultaneously. To prove this, we added white noise to the loop amplifier's bias current to create correlated AM and PM noises. We were able to improve the PM noise by more than 20 dB between 10- and 100-Hz offset frequencies as shown in Fig. 9.

V. IMPROVEMENT OF VIBRATION INSENSITIVITY

An oscillator's phase noise can degrade significantly under vibration compared to its steady-state phase noise. Vibration causes mechanical strain that can introduce either length or size fluctuations, variation in the electrical parameters, parasitic capacitance, and piezoelectric effects in various components in the oscillator circuitry. The amount of degradation in phase noise depends on the oscillator's vibration sensitivity (Γ) defined as

$$\Gamma = \frac{S_\varphi(f)}{\sqrt{S_g(f)}}\left(\frac{f_v}{\nu_0}\right) \quad (1/g) \tag{6}$$

where $S_g(f)$, ν_0, and f_v are, respectively, the power spectral density of acceleration, the carrier frequency, and the vibration frequency. Vibration-induced phase noise can be suppressed either by passive or active vibration-suppression schemes. These schemes have proved very effective for quartz crystal, microwave, and opto-electronic oscillators [19]–[24]. In this

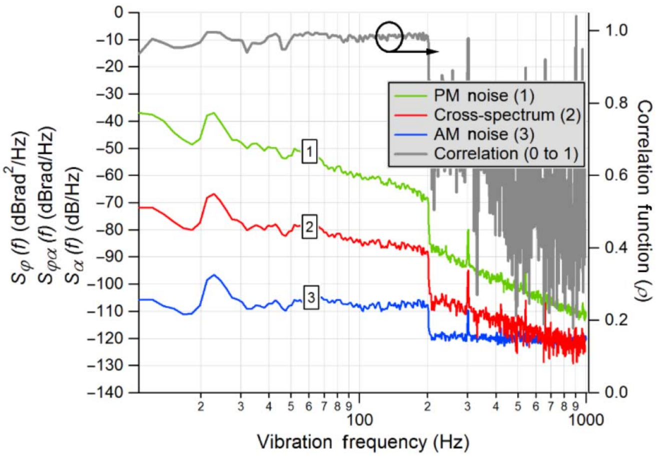


Fig. 10. Plot of PM noise, AM noise, and the CPSD between them for a quartz-MEMS oscillator under vibration. A constant acceleration white noise profile is used. Acceleration $\mathrm{PSD} = 0.005\ \mathrm{g}^2/\mathrm{Hz}$ between 20 and 200 Hz (integrated acceleration $= 0.95\ \mathrm{g_{rms}}$). The plot shows strong correlation ($\rho = 0.97$) within the vibration frequencies (right axis).

section, we report the effect of the correlated PM–AM noise correction scheme discussed in Section II on the vibration sensitivity of a 635-MHz quartz-MEMS oscillator. We mounted a smaller version of the oscillator on a 17.8-cm-diameter shake table. To this point, the steady-state characterization of the oscillator was done with discrete components, and several probes were used to monitor the loop parameters. For the vibration test, we constructed the oscillator using the same resonator; however, surface mount loop components were used for compactness and convenience of mounting the oscillator on this small shake table.

The oscillator was subjected to a constant acceleration white noise of an amount equal to $0.005\ \mathrm{g}^2/\mathrm{Hz}$ between 20 and 200 Hz (integrated acceleration $= 0.95\ \mathrm{g_{rms}}$). Both phase and amplitude noises and CPSD are measured simultaneously and are displayed in Fig. 10. We observe a strong correlation of $\rho > 0.97$ for the frequencies under vibration. As mentioned, vibration causes mechanical distortions and affects the oscillator circuitry. The vibration-induced noise shown in Fig. 11 is the combined contribution from the resonator, electronics components, PCB circuit board, cables, and connectors. Under vibration, we measure the PM noise with and without the feedforward correction. An improvement of almost 15 dB in PM noise is observed over one decade of vibration frequency span as shown in Fig. 11. The vibration sensitivity (Γ) of the oscillator is also shown in Fig. 12, calculated from (6). We demonstrated improvement in the phase noise under vibration as well as in steady-state modes of operation. The phase noise and vibration sensitivity of this oscillator are comparable or superior to other MEMS oscillator when scaled to the same frequency [25]–[28]. For the quartz-MEMS oscillator chosen for the test, the slope between PM and AM noises is not equal under vibration and in the steady-state operation, as a result unique optimization of $H_C(f)$ is required for each operation type to achieve the lowest phase noise.

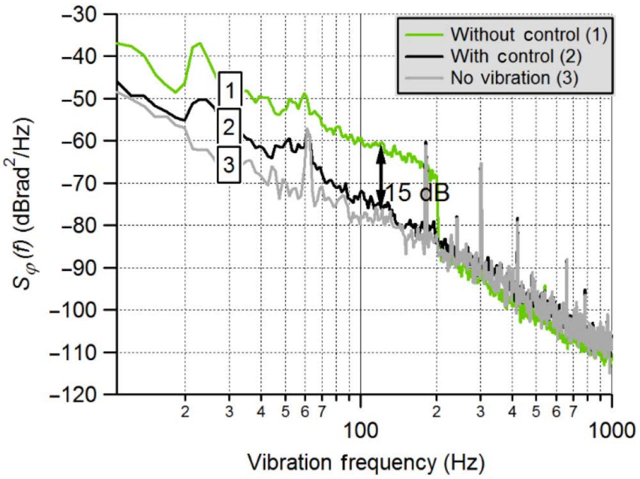


Fig. 11. Plot of PM noise for a quartz-MEMS oscillator at 635 MHz under vibration. (1) With vibration, no feed-forward control, (2) with vibration, with feed-forward control, and (3) no vibration.

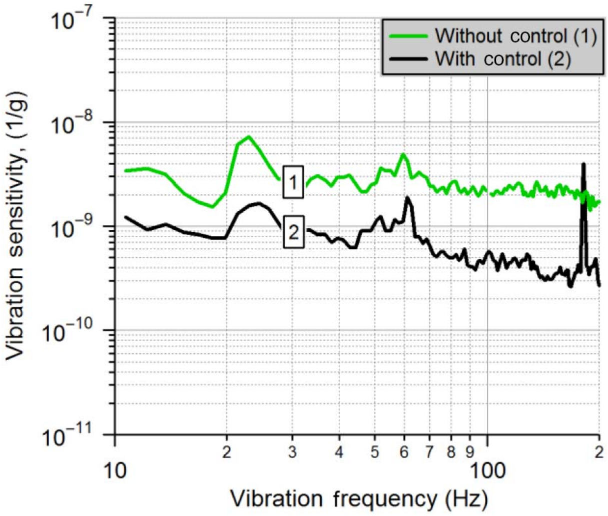


Fig. 12. Vibration sensitivity (Γ) of a quartz-MEMS oscillator at 635 MHz with and without feed-forward cancellation. The two plots are obtained for $S_g(f) = 0.005\ \mathrm{g}^2/\mathrm{Hz}$.

There are advantages of using AM noise as a vibration sensor. In our earlier work [24], we demonstrated a feedforward electronic phase correction scheme for the mitigation of vibration-induced phase fluctuations in an optoelectronic oscillator (OEO) [29]. Instead of using the AM noise as a vibration sensor, an accelerometer was used. While the oscillator was under vibration, an estimate of a complex-conjugate (same amplitude and opposite phase) signal was generated from accelerometer signals and used to modulate the oscillator's output phase in a feedforward method to suppress or reduce the induced noise sidebands.

Schemes that use accelerometers as vibration sensors have proven to be effective, but their main drawback is the dependence on position and mounting of the sensor. In our new scheme, the vibration detection occurs in the oscillator itself, which removes the difficulty of having to find the optimal position or mounting of the sensor. An accelerometer-based correction requires sensing of vibration and generation of the control signal independently for all six degrees of freedom (x, y, z linear and orthogonal axes). The feedforward correction via PM–AM noise correlation in this paper may correct all degrees of freedom of the correlated Γ simultaneously. We intend to address this possible advantage in a future study.

VI. CONCLUSION

We presented results that show how phase fluctuations of an oscillator can be compensated from correlated amplitude fluctuations. A simple scheme was described that is effective under steady-state conditions, as well as under vibration. We implemented this noise-reducing scheme in a MEMS oscillator and showed that the PM noise reduces by more than 10 dB under quiet and vibrating operating conditions.

Previous studies of the correlation between PM and transistor current noise to improve 1/*f* phase noise in transistors and its application to reduce the frequency fluctuations in an oscillator are known [30], [31]. These schemes only reduce phase noise from correlations that exist in the loop amplifier (from transistor bias current noise). Our scheme reduces the phase noise of an oscillator if this correlation originates from the amplifier, resonator, phase shifter, or all components simultaneously.

Like all correlation cancellation techniques, the degree of PM noise improvement is reduced if an oscillator lacks correlation between PM and AM noises, or if this correlation is not stable with time and environmental extremes.

ACKNOWLEDGMENT

The authors would like to thank D. Chang and H. Moyers of HRL Laboratories, LLC for providing the 635-MHz quartz-MEMS resonator. They would also like to thank F. Quinlan and F. Walls for helpful comments on this paper, and D. Lirette, W. M. Haynes, and M. Lombardi for help with preparation and editing this work.

REFERENCES

[1] E. D. Kaplan, *Understanding GPS: Principles and Applications*, 2nd ed. Norwood, MA, USA: Artech House, 2005.

[2] M. A. Richards, J. A. Scheer, and W. A. Holm, Eds., *Principles of Modern Radar: Basic Principles*. Raleigh, NC, USA: SciTech Publishing, 2010.

[3] J. B. Campbell and R. H. Wynne, *Introduction to Remote Sensing*, 5th ed. New York, NY, USA: The Guilford Press, 2011.

[4] G. L. Charvat, *Small and Short-Range Radar Systems*, 1st ed. Boca Raton, FL, USA: CRC Press, 2014.

[5] W. Tomasi, *Advanced Electronic Communications Systems*, 6th ed. Englewood Cliffs, NJ, USA: Prentice Hall, 2003.

[6] C. McNeilage, E. N. Ivanov, P. R. Stockwell, and J. H. Searls, "Review of feedback and feedforward noise reduction techniques," in *Proc. IEEE Int. Freq. Control Symp.*, 1998, pp. 146–155.

[7] F. L. Walls, E. S. Ferre-Pikal, and S. R. Jefferts, "Origin of 1/f PM and AM noise in bipolar junction transistor amplifiers," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 44, no. 2, pp. 326–334, Mar. 1997.

[8] L. M. Nelson, C. W. Nelson, and F. L. Walls, "Relationship of AM to PM noise in selected RF oscillators," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 41, no. 5, pp. 680–684, Sep. 1994.

[9] R. Boudot and E. Rubiola, "Phase noise in RF and microwave amplifiers," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 59, no. 12, pp. 2613–2624, Dec. 2012.

[10] M. M. Driscoll, "Oscillator AM-to-FM noise conversion due to the dynamic frequency-drive sensitivity of the crystal resonator," in *Proc. IEEE Int. Freq. Control Symp.*, 2008, pp. 672–676.

[11] E. Hegazi and A. A. Abidi, "Varactor characteristics, oscillator tuning curves, and AM-FM conversion," *IEEE J. Solid-State Circuits*, vol. 38, no. 6, pp. 1033–1039, Jun. 2003.

[12] M. Agarwal *et al.*, "Amplitude noise induced phase noise in electrostatic MEMS resonators," in *Proc. Solid State Sensor Actuator Microsyst. Workshop*, Hilton Head, SC, USA, 2008, pp. 90–93.

[13] D. T. Chang *et al.*, "Nonlinear UHF quartz MEMS oscillator with phase noise reduction," in *Proc. IEEE 26th Int. Conf. Micro Electro Mech. Syst. (MEMS)*, 2013, pp. 781–784.

[14] D. A. Howe, A. Hati, C. W. Nelson, and D. Lirette, "PM-AM correlation measurements and analysis," in *Proc. IEEE Int. Freq. Control Symp. (FCS)*, 2012, pp. 1–5.

[15] A. Hati, C. W. Nelson, and D. Howe, "Correlation measurements between PM and AM noise in oscillators," in *Proc. IEEE Int. Freq. Control Symp. (FCS)*, 2014, pp. 1–3.

[16] A. Hati, C. W. Nelson, and D. Howe, "Reducing oscillator PM noise from AM-PM noise correlation," *Electron. Lett.*, vol. 50, no. 17, pp. 1195–1197, Aug. 2014.

[17] F. L. Walls, "Correlation between upper and lower sidebands," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 47, no. 2, pp. 407–410, Mar. 2000.

[18] D. B. Leeson, "A simple model of feedback oscillator noise spectrum," *Proc. IEEE*, vol. 54, no. 2, pp. 329–330, Feb. 1966.

[19] R. L. Filler, "The acceleration sensitivity of quartz crystal oscillators: A review," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 35, no. 3, pp. 297–305, May 1988.

[20] M. B. Bloch, J. C. Ho, C. S. Stone, A. Syed, and F. L. Walls, "Stability of high quality quartz crystal oscillators: An update," in *Proc. 43rd Annu. Symp. Freq. Control*, Denver, CO, USA, 1989, pp. 80–84.

[21] D. A. Howe, J. L. LanFranchi, L. Cutsinger, A. Hati, and C. Nelson, "Vibration-induced PM noise in oscillators and measurements of correlation with vibration sensors," in *Proc. IEEE Int. Freq. Control Symp. Expo.*, 2005, p. 5.

[22] M. M. Driscoll, "Reduction of quartz crystal oscillator flicker-of-frequency and white phase noise (floor) levels and acceleration sensitivity via use of multiple resonators," in *Proc. IEEE 46th Freq. Control Symp.*, 1992, pp. 334–339.

[23] J. A. Kosinski, "Theory and design of crystal oscillators immune to acceleration: Present state of the art," in *Proc. IEEE/EIA Int. Freq. Control Symp. Exhibit.*, 2000, pp. 260–268.

[24] A. Hati, C. W. Nelson, J. Taylor, N. Ashby, and D. A. Howe, "Cancellation of vibration-induced phase noise in optical fibers," *IEEE Photon. Technol. Lett.*, vol. 20, no. 22, pp. 1842–1844, Nov. 2008.

[25] A. Tazzoli *et al.*, "Piezoelectric nonlinear nanomechanical temperature and acceleration insensitive clocks," in *Proc. SPIE Defense Secur. Sens.*, 2012, p. 83730A.

[26] S. Lee and C. T.-C. Nguyen, "Phase noise amplitude dependence in self-limiting wine-glass disk oscillators," presented at the Solid- State Sensor, Actuator, and Microsystems Workshop, 2004, pp. 33–36.

[27] B. Kim, R. H. Olsson, K. Smart, and K. E. Wojciechowski, "MEMS resonators with extremely low vibration and shock sensitivity," in *Proc. IEEE Sensors*, 2011, pp. 606–609.

[28] SiTime. (2014). *Shock and Vibration Comparison of MEMS and Quartz-Based Oscillators* [Online]. Available: http://www.sitime.com/support/application-notes

[29] X. S. Yao and L. Maleki, "Optoelectronic microwave oscillator," *J. Opt. Soc. Amer. B*, vol. 13, no. 8, pp. 1725–1735, Aug. 1996.

[30] K. Takagi, S. Serikawa, and A. Okuno, "1/f phase noise in a transistor and its application to reduce the frequency fluctuation in an oscillator," *Microelectron. Reliab.*, vol. 40, no. 11, pp. 1943–1950, Nov. 2000.

[31] K. Takagi, S. Serikawa, and T. Doi, "A method to reduce the phase noise in bipolar transistor circuits," *IEEE Trans. Circuits Syst. II: Analog Digit. Signal Process.*, vol. 45, no. 11, pp. 1505–1507, Nov. 1998.

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