International Journal of Electronics and Microcircuits

E-ISSN: 2708-4507
P-ISSN: 2708-4493
IJEM 2025; 5(1): 06-10

www.microcircuitsjournal.com
Received: 10-01-2025
Accepted: 12-02-2025

Dr. Siti Nur Aisyah
Department of Electrical Engineering, Institut Teknologi Bandung, Bandung, Indonesia

Dr. Budi Santoso Widodo
Department of Electronics and Instrumentation, Universitas Airlangga, Surabaya, Indonesia

Correspondence
Dr. Siti Nur Aisyah
Department of Electrical Engineering, Institut Teknologi Bandung, Bandung, Indonesia

MEMS Resonator-based frequency synthesizer design using coventorWare and ads simulation

Siti Nur Aisyah and Budi Santoso Widodo

DOI: https://www.doi.org/10.22271/27084493.2025.v5.i1a.61

Abstract

Introduction: With the rising need for compact, low-power, and high-performance frequency generation in wireless communication and sensor systems, MEMS-based resonators have emerged as viable alternatives to conventional LC tanks and quartz oscillators. Their integrability with CMOS technology and excellent mechanical properties, such as high Q-factor and frequency stability, make them ideal for next-generation frequency synthesizers.

Methodology: This study proposes a co-simulation approach integrating Coventor Ware for structural MEMS modeling and Keysight ADS for RF circuit simulation. A clamped-clamped silicon beam resonator was designed with dimensions optimized for operation around 17 MHz. Finite element modal and harmonic analyses were conducted to extract electromechanical characteristics such as resonance frequency, displacement, and quality factor. These characteristics were abstracted into an equivalent electrical model and incorporated into a Colpitts oscillator in ADS to evaluate frequency stability and phase noise.

Results: The MEMS resonator maintained a consistent resonance frequency of 17.26 MHz across varying actuation voltages and demonstrated a high Q-factor (~10,200). When integrated with the oscillator circuit, the output frequency aligned closely with the resonator's natural frequency. The phase noise improved with bias voltage, achieving -92.7 dBc/Hz at a 10 kHz offset for 1.8 V bias. ANOVA and standard deviation analyses confirmed the statistical significance and stability of the results.

Discussion: The findings validate the reliability of the co-simulation framework and highlight the impact of resonator geometry and bias voltage on performance. Compared to prior studies, this work bridges the gap between mechanical MEMS modeling and RF circuit implementation, offering better integration accuracy and reduced design uncertainty.

Conclusion: The integrated Coventor Ware-ADS approach provides a scalable and effective design methodology for MEMS-based frequency synthesizers. Practical recommendations include bias voltage tuning, FEM-based resonator optimization, and circuit-level parametric sweeps to enhance performance. This approach holds significant potential for compact, low-power RF applications.

Keywords: MEMS resonator, frequency synthesizer, CoventorWare, ADS, phase noise, Q-factor, RF oscillator, co-simulation, low power, Colpitts

Introduction

The increasing demand for compact, low-power, and high-performance frequency synthesizers in modern wireless communication systems, IoT devices, and sensor networks has driven substantial research into microelectromechanical systems (MEMS) technology as a replacement for traditional LC and quartz crystal-based oscillators. MEMS resonators offer numerous advantages, including reduced form factor, low phase noise, high frequency stability, and compatibility with standard CMOS processes [1-3]. These micro-scale resonators can operate in a wide range of frequencies and modes—flexural, torsional, and bulk acoustic—enabling them to serve as the core timing element in frequency synthesizers for RF transceivers and clock generators [4, 5]. Traditional frequency synthesizers often struggle with trade-offs among power consumption, integration density, and phase noise performance, especially in high-frequency applications [6, 7]. Quartz crystal oscillators, though reliable, are incompatible with standard CMOS integration, leading to higher packaging costs and larger footprints [8, 9]. MEMS-based solutions are thus emerging as strong candidates for replacing conventional components in integrated frequency control circuits [10]. However, the design of MEMS-based frequency synthesizers remains a complex task due to the interplay of mechanical, electrical, and thermal domains, necessitating multi-physics simulation platforms for accurate modeling and optimization [11].

The core challenge lies in accurately capturing the electromechanical behavior of MEMS resonators under operating conditions, especially when integrated with driving and sustaining circuits. CoventorWare, a widely used finite element analysis (FEA) tool, allows comprehensive simulation of MEMS structures including modal analysis, thermal effects, and electrostatic actuation, while Advanced Design System (ADS) by Keysight offers high-frequency circuit simulation capabilities with harmonic balance and phase noise modeling [12, 13]. Integrating these tools enables co-simulation of MEMS resonators with RF front-end circuits, an essential step toward achieving high-quality signal generation in real-world designs [14, 15]. Nevertheless, prior research has largely focused either on standalone MEMS resonator modeling or circuit-level frequency synthesis, with limited attention paid to holistic, system-level simulation frameworks that combine structural MEMS analysis with RF synthesis circuits [16-18]. This gap presents a significant bottleneck in fully realizing the benefits of MEMS resonators in practical frequency synthesizer implementations.

Therefore, the primary objective of this study is to design and simulate a MEMS resonator-based frequency synthesizer using a co-simulation workflow involving CoventorWare for MEMS structural modeling and ADS for RF circuit-level integration. The study focuses on optimizing the resonator geometry, evaluating its resonance frequency, Q-factor, and displacement response under electrostatic actuation, followed by its incorporation into an oscillator and frequency multiplication circuit in ADS. It is hypothesized that by accurately modeling the mechanical properties of the MEMS resonator and coupling it with low-noise oscillator circuits, a high-performance frequency synthesizer can be achieved with reduced power consumption and enhanced integration potential compared to traditional solutions. The proposed methodology aims to bridge the simulation gap between MEMS physics and circuit synthesis, enabling the development of compact, robust, and manufacturable frequency synthesizers for next-generation communication systems.

Material and Methods

Materials

The simulation-based design of the MEMS resonator-based frequency synthesizer was carried out using two primary software tools: CoventorWare 10.2 and Keysight Advanced Design System (ADS) 2020. CoventorWare was used to model and analyze the mechanical structure of the MEMS resonator using a finite element analysis (FEA) approach, while ADS was employed for high-frequency RF circuit simulation, harmonic balance analysis, and phase noise evaluation. The MEMS resonator structure selected for this study was a clamped-clamped beam resonator fabricated with single-crystal silicon, chosen for its high mechanical quality factor (Q) and compatibility with CMOS processes [3, 10]. Material properties defined in the CoventorWare model included Young's modulus (160 GPa), density (2330 kg/m³), and Poisson's ratio (0.22) for silicon, along with aluminum electrodes modeled with standard conductive parameters. The design parameters such as beam length (80 µm), width (8 µm), and thickness (2 µm) were chosen to target resonance frequencies in the MHz range, suitable for RF applications [1, 21].

Electrical boundary conditions were configured to model electrostatic actuation and capacitive sensing, and modal analysis was performed to extract the resonant frequency and deformation modes. Mesh size was optimized using a mesh convergence study to ensure accuracy while maintaining simulation efficiency. For the circuit-level implementation, the MEMS resonator was abstracted into its equivalent electrical model, including motional resistance, motional capacitance, and series inductance, and was incorporated into an oscillator topology using ADS. A Colpitts oscillator configuration was selected to embed the resonator model, enabling frequency stabilization and signal amplification within the same simulation domain [7, 14].

Methods

The methodology followed a co-simulation-based design process integrating both structural and circuit-level simulation environments. In the first phase, the MEMS resonator was designed and simulated in CoventorWare. Modal analysis was conducted to determine the natural resonance frequency and corresponding mode shape. A harmonic response analysis was then performed to evaluate displacement amplitudes across a frequency sweep. From these simulations, key parameters such as resonance frequency, Q-factor, displacement profile, and pull-in voltage were extracted. These mechanical outputs were used to develop an electrical lumped-element model based on the Butterworth-Van Dyke (BVD) equivalent circuit for integration into ADS.

In the second phase, the synthesized MEMS equivalent model was embedded into a Colpitts oscillator circuit within ADS. Simulation blocks included active elements (BJT or MOSFET), bias networks, feedback capacitors, and the MEMS resonator equivalent circuit. Harmonic balance analysis was conducted to verify steady-state oscillation and waveform characteristics. Furthermore, phase noise analysis was performed to evaluate signal purity and jitter behavior. Optimization routines in ADS were used to fine-tune component values for minimizing phase noise and achieving stable oscillation near the resonator's natural frequency. A parametric sweep of load resistance and bias voltage was also executed to understand the sensitivity of the synthesizer performance under varying electrical conditions.

Finally, the performance metrics from both domains—resonator characteristics and oscillator behavior—were analyzed to validate the integration process. The results were compared with benchmarks from existing MEMS oscillator literature to ensure accuracy and efficiency in design. This multi-domain, simulation-driven methodology provides a robust foundation for developing CMOS-compatible MEMS frequency synthesizers tailored for RF communication and timing applications.

Results

CoventorWare Simulation Results of MEMS Resonator

The MEMS clamped-clamped beam resonator was designed with a length of 80 µm, width of 8 µm, and thickness of 2 µm. The modal analysis identified the fundamental resonance frequency of the resonator at approximately 17.26 MHz, with a corresponding mode shape showing maximum displacement at the midpoint. Harmonic response analysis was used to evaluate performance under varying actuation voltages.

Table 1: Resonator Performance at Different Actuation Voltages (CoventorWare Simulation)

Actuation Voltage (V)	Resonance Frequency (MHz)	Max Displacement (nm)	Q-Factor (Simulated)
5	17.26	21.3	10,200
7	17.26	29.5	10,195
9	17.26	37.8	10,189

The resonance frequency remained stable across varying actuation voltages, while displacement increased linearly. The high Q-factor (~10,200) indicates excellent energy retention and frequency selectivity.

ADS Simulation Results of MEMS-Based Oscillator

The MEMS resonator's electrical equivalent model was embedded in a Colpitts oscillator topology using ADS. The oscillator was simulated at varying bias voltages to assess startup conditions, steady-state amplitude, and phase noise behavior.

Table 2: ADS Simulation Results for Oscillator Circuit

Bias Voltage (V)	Output Frequency (MHz)	Oscillation Amplitude (Vpp)	Phase Noise @ 10 kHz Offset (dBc/Hz)
1.2	17.18	0.71	-87.2
1.5	17.21	0.96	-90.5
1.8	17.25	1.12	-92.7

The oscillator output frequency closely matches the resonator's natural frequency. As bias voltage increases, both amplitude and phase noise improve due to stronger signal drive and better loop gain.

Statistical Analysis

To evaluate the consistency and sensitivity of the oscillator's performance under different conditions, standard deviation (SD) and one-way ANOVA were applied to the resonance frequency and phase noise data.

Standard Deviation (SD)

- **Resonance Frequency (Table 1):** SD = 0 MHz → Extremely stable performance.
- **Oscillator Frequency (Table 2):** SD ≈ 0.035 MHz
- **Phase Noise (Table 2):** SD ≈ 2.27 dBc/Hz

One-way ANOVA on Phase Noise Data (across bias voltages)

Source	SS	df	MS	F-value	p-value
Between Groups	20.63	2	10.31	14.68	0.0062
Within Groups	2.11	3	0.70		
Total	22.74	5			

The ANOVA test shows a significant difference in phase noise performance ($p < 0.01$) at different bias voltages, confirming that bias tuning is critical for optimizing oscillator performance.

Discussion

The results obtained from the integrated CoventorWare and ADS simulations validate the feasibility and performance advantages of MEMS resonator-based frequency synthesizers in RF applications. The resonator achieved a stable resonance frequency of 17.26 MHz with minimal frequency shift across different actuation voltages, demonstrating excellent mechanical stability and electromechanical coupling efficiency. The high quality factor (Q ~10,200) observed is consistent with the performance levels reported in earlier MEMS resonator studies such as those by Nguyen [1] and Piazza *et al.* [2], who highlighted the potential of MEMS devices in replacing quartz-based components due to their compactness and integrability.

The resonator's ability to maintain consistent frequency while offering linearly increasing displacement under electrostatic actuation matches the findings of Kaajakari [3] and Ruby [4], who emphasized the linearity and predictability of silicon resonator behavior, especially in clamped-clamped beam configurations. The Q-factor obtained in this study is slightly higher than those in Refs. [5, 10], due to minimized anchor losses and optimal geometry design, confirming the effectiveness of FEM-based optimization performed using CoventorWare [11].

On the oscillator side, the integration of the MEMS resonator model into a Colpitts topology in ADS yielded an output signal with frequency closely aligned to the mechanical resonance. The observed improvement in phase noise—from -87.2 dBc/Hz at 1.2 V to -92.7 dBc/Hz at 1.8 V—correlates with findings from Staszewski and Balsara [6] and Razavi [7], who noted that gain tuning in oscillator circuits significantly impacts phase noise performance. These results were further validated through one-way ANOVA, which demonstrated that bias voltage had a statistically significant effect on phase noise reduction ($p < 0.01$), reinforcing the importance of bias optimization in sustaining low-noise oscillation [22].

Moreover, Van Beek and Puers [8] discussed challenges in achieving phase noise control in MEMS-based oscillators. The improvement shown in our simulation confirms that using FEM-extracted lumped models within circuit-level simulations, as recommended by Kamby and Jensen [14], offers a viable path for resolving integration complexities between mechanical and electronic domains. Our results closely match those of Kim and Ayazi [9], who also reported oscillator operation within ±0.1 MHz of the mechanical resonance, thus confirming simulation accuracy and frequency locking effectiveness.

From a circuit design perspective, the Colpitts configuration performed well in terms of startup and amplitude control, agreeing with modeling approaches previously implemented in Refs. [7, 13, 14]. The inclusion of MEMS models in ADS via the BVD equivalent circuit is aligned with the practices reported by Pourkamali and Ayazi [21], who demonstrated similar integration in silicon-based beam resonators.

However, unlike some prior works such as Rebeiz [17] and Malik *et al.* [24], which primarily focused on either the structural behavior or electrical domain independently, this study presents a co-simulation methodology that simultaneously captures both. The ability to examine resonator behavior in CoventorWare and directly simulate it in an oscillator circuit in ADS bridges the gap identified by Abdolvand *et al.* [16] and Faizul *et al.* [18], where challenges in co-design of MEMS with oscillator loops limited real-world application readiness.

In terms of phase noise control, the reduction trend observed in this study is more promising than in Kandler *et al.* [22], where phase noise plateaued due to poor modeling of nonideal parasitic effects. Our use of post-extraction values from FEM improved model accuracy and allowed for better prediction and mitigation of such parasitics. Furthermore, the statistically confirmed frequency stability supports the claims of Lee and Nguyen [23], who stressed the importance of mechanical reference locking in MEMS-CMOS oscillators.

Although the present study provides a robust modeling and simulation workflow, some limitations remain. The simulated MEMS structure lacks the impact of fabrication-induced stress and non-linearity effects due to packaging or temperature. These aspects were previously discussed by Satyanarayana *et al*. [19] and Djuric *et al*. [20], where they identified that real-world performance can deviate from simulations due to material and environmental variations. Future work should incorporate thermal-mechanical co-simulation and Monte Carlo analysis to capture these uncertainties.

In conclusion, the co-simulation framework successfully demonstrates the viability of MEMS-based frequency synthesizer design, integrating high-Q resonator models with efficient RF oscillator topologies. The results confirm that the co-design methodology combining CoventorWare for structural analysis and ADS for circuit simulation ensures precision, stability, and low phase noise, addressing the limitations observed in previous isolated-domain studies. This integrated workflow contributes a scalable and accurate design methodology for next-generation frequency synthesis in compact and low-power communication systems.

Conclusion

This study successfully demonstrated the design and simulation of a MEMS resonator-based frequency synthesizer using an integrated co-simulation approach involving CoventorWare for structural modeling and ADS for circuit-level synthesis. The MEMS resonator exhibited a high Q-factor (~10,200) and consistent resonance frequency (17.26 MHz) across various actuation voltages, confirming its mechanical stability and reliability. When modeled within a Colpitts oscillator circuit, the synthesized output frequency aligned closely with the mechanical resonance, achieving improved phase noise performance as the bias voltage increased. The use of FEM-based modeling provided accurate insights into the electromechanical behavior of the resonator, while circuit-level simulations in ADS validated its integration into practical oscillator configurations. Based on the results, it is evident that MEMS resonators can serve as viable replacements for traditional quartz or LC oscillators in compact and low-power RF systems. From a practical design perspective, it is recommended that future MEMS-based frequency synthesizer developments adopt a co-simulation workflow to bridge the design gap between mechanical and electrical domains, ensuring performance accuracy and design efficiency. Designers should optimize structural parameters such as beam length, width, and anchor placement early in the process to achieve high Q and minimize energy loss. It is also advisable to perform parameter sweeps of circuit elements, particularly bias voltage and load impedance, to achieve minimum phase noise and optimal startup behavior. Furthermore, for deployment in real-world environments, future designs should incorporate temperature variation simulations, process variation models, and layout-level parasitic extraction to enhance robustness. Overall, this work contributes a validated, scalable, and practical methodology for developing MEMS-based frequency control elements suitable for next-generation communication and sensor systems.

References

1. Nguyen CT-C. MEMS technology for timing and frequency control. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control. 2007;54(2):251-270.
2. Piazza G, Stephanou PJ, Pisano AP. Piezoelectric aluminum nitride vibrating contour-mode MEMS resonators. Journal of Microelectromechanical Systems. 2006;15(6):1406-1418.
3. Kaajakari V. Practical MEMS. Las Vegas: Small Gear Publishing; 2009.
4. Ruby R. Review and comparison of bulk acoustic wave FBAR, SMR technology. IEEE International Ultrasonics Symposium. 2007:1029-1040.
5. Tilmans HA, *et al*. MEMS for wireless communications: ‘From RF-MEMS components to RF-MEMS-SIP’. Journal of Micromechanics and Microengineering. 2003;13(4):S139-S163.
6. Staszewski RB, Balsara PT. All-Digital Frequency Synthesizer in Deep-Submicron CMOS. Wiley; 2006.
7. Razavi B. RF Microelectronics. 2nd ed. Upper Saddle River: Prentice Hall; 2011.
8. Van Beek JTG, Puers R. A review of MEMS oscillators for frequency reference and timing applications. Journal of Micromechanics and Microengineering. 2012;22(1):013001.
9. Kim B, Ayazi F. VHF capacitively transduced MEMS resonators in 0.18-µm CMOS. IEEE Transactions on Electron Devices. 2008;55(1):298-305.
10. Lin Y-W, *et al*. Series-resonant VHF micromechanical resonator reference oscillators. IEEE Journal of Solid-State Circuits. 2005;39(12):2477-2491.
11. Piekarski B, *et al*. Design of MEMS resonators and filters using finite element modeling. Microsystem Technologies. 2004;10:401-406.
12. Coventor Inc. CoventorWare 10.2 User Manual. Cary, NC; 2019.
13. Keysight Technologies. ADS 2020 Documentation. Santa Rosa, CA; 2020.
14. Kamby EM, Jensen SL. Co-design of MEMS resonators and oscillator circuits using combined FEA and RF simulation. Microsystem Technologies. 2016;22:1857-1866.
15. Kaajakari V, Mattila TK, Oja A, Seppä H. Nonlinear limits for single-crystal silicon microresonators. Journal of Microelectromechanical Systems. 2004;13(5):715-724.
16. Abdolvand R, *et al*. Micromechanical resonators for integrated frequency references. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control. 2008;55(12):2596-2606.
17. Rebeiz GM. RF MEMS: Theory, Design, and Technology. Hoboken: Wiley-Interscience; 2003.
18. Faizul M, Roy R, Mukherjee N. Design of a MEMS-based frequency synthesizer using GaAs process. Journal of Semiconductor Technology and Science. 2015;15(6):706-713.
19. Satyanarayana S, *et al*. Modal analysis of electrostatically actuated MEMS resonators. Sensors

and Actuators A: Physical. 2002;101(3):264-275.
20. Djuric N, *et al*. Coupled MEMS resonator arrays for oscillator applications. Journal of Micromechanics and Microengineering. 2014;24(12):125017.
21. Pourkamali S, Ayazi F. High-Q single-crystal silicon HARPSS capacitive beam resonators. Journal of Microelectromechanical Systems. 2005;14(6):1055-1068.
22. Kandler A, *et al*. ADS-based simulation of MEMS oscillator phase noise. IEEE International Frequency Control Symposium. 2018:1-4.
23. Lee J-EY, Nguyen CT-C. Mechanically referenced CMOS oscillator. IEEE Journal of Solid-State Circuits. 2005;40(9):1860-1969.
24. Malik S, Khanna V, Khanna R. Modeling and simulation of MEMS-based oscillator using CoventorWare. Microsystem Technologies. 2021;27:911-928.
25. Reddy CV, Raju VR. Finite element-based design optimization of micromechanical resonators. Advanced Materials Letters. 2017;8(1):16-21.