Advanced Control Engineering for Frequency Stability in Quartz Oscillators

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***Abstract*— Quartz oscillators have been central to frequency control for decades, providing stability and precision in both ground and space applications. With the increasing demand for ultra-high stability, advanced control science engineering has become essential in the design and optimization of these oscillators. This paper reviews significant progress in control methodologies applied to quartz resonators and oscillators, focusing on temperature compensation, drive-level dependence, and phase noise reduction. We summarize recent contributions in the field and highlight the role of system engineering in enhancing stability performance for critical applications.**

Keywords : Quartz; Oscillators; Control engineering

I. Introduction

Quartz crystal oscillators remain among the most reliable and stable frequency sources for timekeeping, communications, and metrology. Despite the emergence of optical frequency standards, ultra-stable quartz oscillators continue to provide unmatched performance in compact and robust designs [1,2]. Control science engineering plays a decisive role in pushing stability limits, enabling better modeling, compensation, and optimization strategies.

The development of ultra-precise oscillators has historically been driven by space missions and military applications [2]. More recently, new requirements in navigation systems, telecommunications, and scientific instrumentation have motivated enhanced designs that integrate frequency control, thermal management, and system-level optimization [3,4].

In this paper, after reminding the background about quartz oscillators, we investigate control science engineering including at the system level and the possible future trends.

II. Background on ultra-stable oscillators

In this part, we discuss how quartz resonators exploit the piezoelectric effect to achieve high quality factors (Q) and frequency selectivity. Among them, BVA (In French: *Boîtier à Vieillissement Amélioré*) resonators, introduced by R. Besson [5], have demonstrated record levels of frequency stability. Key performance metrics include short-term stability, long-term aging, and sensitivity to environmental perturbations. A landmark advancement was reported in [1], where optimized control strategies led to unprecedented stability at the 2.5×10^{-14} level over 20 s integration time. This step marked a new benchmark in oscillator design, consolidating quartz technology's position despite competition from emerging alternatives.

Quartz oscillators are foundational components in precision timing and frequency control, exploiting the piezoelectric effect to convert electrical signals into mechanical vibrations and vice versa [6]. This property enables quartz resonators to achieve extremely high-quality factors (Q), which directly translate to low phase noise and high frequency selectivity. Among the various resonator types, BVA quartz resonators have consistently demonstrated exceptional frequency stability, making them the preferred choice for ultra-stable oscillator designs. In reference [4] authors measured phase noise of 5 MHz BVA quartz crystals and reported some of the lowest noise floors achievable at the time, highlighting the resonator's superior performance in high-precision applications.

The performance of ultra-stable quartz oscillators is commonly evaluated through several key metrics:

Short-term stability, typically characterized by the Allan deviation over integration times ranging from 1 s to a few hundred seconds. This metric captures the oscillator's susceptibility to rapid fluctuations and environmental noise.

Long-term aging, reflecting frequency drift over months or years due to internal material changes and stress relaxation in the crystal.

Environmental sensitivity, including the influence of temperature, vibration, and pressure variations. High-performance BVA resonators are often operated in temperature-controlled ovens (OCXOs) or vacuum-packaged assemblies to minimize these effects.

A major milestone in ultra-stable oscillator development was reported in [1], where optimized control strategies, including precise thermal regulation, advanced electronic compensation, and refined crystal cut techniques, enabled frequency stability at the 2.5×10^{-14} level over 20 s integration time. This represents a substantial improvement over earlier designs and established a new benchmark for quartz oscillator performance, effectively solidifying quartz technology's dominance despite the emergence of competing technologies such as atomic vapor-cell and optical cavity oscillators.

The continued evolution of ultra-stable quartz oscillators combines material science, precision engineering, and advanced control electronics, allowing their integration into demanding applications such as deep-space navigation, metrology, and high-end telecommunications, where even nanohertz-level frequency drifts are critical.

III. Control Science Engineering in Frequency Stability

The application of control science engineering to quartz oscillators involves modeling and controlling nonlinear effects, optimizing temperature and frequency control loops, and minimizing drive-level sensitivity.

III.1. Temperature Compensation

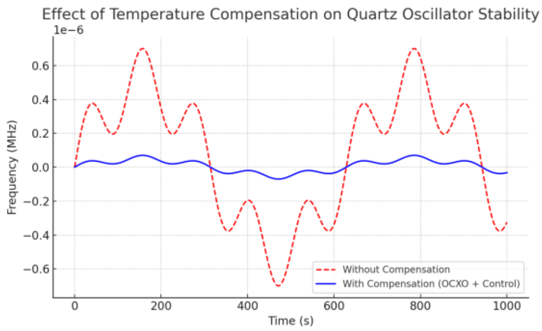

Fig.1. Temperature compensation (e.g., OCXOs with control engineering) suppresses frequency drift caused by environmental temperature fluctuations.

Temperature fluctuations are a dominant source of frequency instability. Methods for compensation include oven-controlled crystal oscillators (OCXOs) and advanced temperature modeling approaches [7].

Control theory enables fine-tuning of thermal dynamics, ensuring minimal deviations in oscillator frequency. It is illustrated ion Fig. 1.

III.2. Drive-Level Dependence

The dependence of quartz resonators on drive level at very low excitation is a critical limitation for precision oscillators. A review presented in [7] and discussed in [8] highlighted the nonlinear behavior of resonators under varying excitation, underlining the importance of maintaining optimal operating regimes through control strategies and nonlinear dependence is illustrated in Fig. 2.

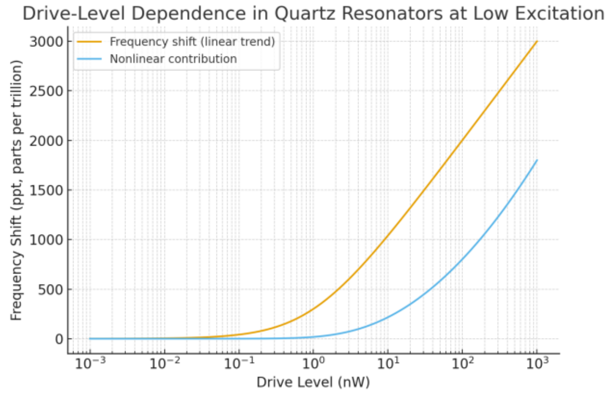

Fig. 2. Nonlinear dependence of quartz resonators on drive level at very low excitation. It shows both a general linear trend in frequency shift and the nonlinear contribution that becomes significant, highlighting why maintaining an optimal operating regime is critical for precision oscillators.

III.3. Phase Noise and Short-Term Stability

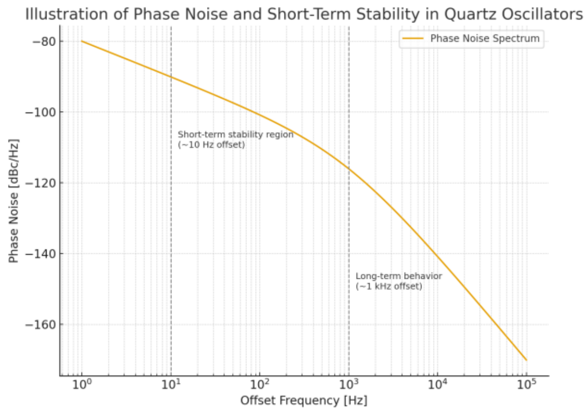

Fig. 3. Relationship between phase noise and short-term stability in quartz oscillators. It shows how the close-in phase noise (near 10 Hz offset) directly relates to short-term stability, while the far-out region (around 1 kHz and beyond) reflects longer-term behavior. For Fourier frequencies over 10^4, there are other limitation.

Phase noise directly impacts the short-term stability of oscillators as given in Fig. 3. Similarly, experimental studies such as [9] demonstrated the metrological importance of phase noise in 10 MHz BVA resonators. The methodology reported in [10] provides a computation framework linking passive phase noise measurements to resonator performance, offering an essential tool for control engineers. Quartz crystal oscillators have undergone significant evolution since their inception, enabling increasingly precise timekeeping systems [11]. Efforts to improve their performance have included detailed studies on minimizing intrinsic noise sources, particularly 1/f noise in both amplifiers and bulk acoustic wave (BAW) quartz oscillators, which remains a critical factor in oscillator stability [12].

IV. System-Level Engineering

Control engineering extends beyond resonator physics to encompass complete system design. Complex systems in optoelectronics and electronics require integrated control approaches for frequency and temperature [4]. Recent progress in simulation-based optimization has enhanced the ability to predict performance and oscillator behavior to specific applications. Control engineering has evolved beyond the fundamental physics of quartz resonators to encompass comprehensive system design, integrating various components to achieve optimal performance. In complex systems, the interplay between quartz oscillators and electronic circuits necessitates a holistic approach to ensure stability and accuracy. Quartz oscillators, known for their precision and reliability, serve as the heartbeat of many electronic systems, from communication devices to scientific instruments [13-15].

Fig. 4 summarizes the main principle of controlling the temperature effects and the need to model the effects.

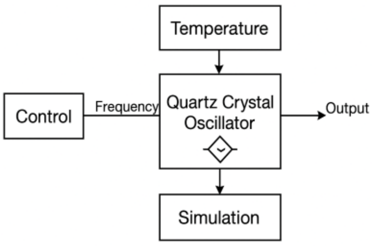

Fig. 4. A system level approach for improving the oscillator.

The frequency stability of quartz oscillators is inherently influenced by temperature variations. As temperature changes, the physical dimensions of the quartz crystal alter, leading to shifts in the oscillation frequency. This phenomenon, known as the frequency-temperature (f-T) characteristic, poses challenges in applications requiring high precision. To mitigate these effects, advanced control engineering techniques are employed. For instance, Temperature Compensated Crystal Oscillators (TCXOs) utilize temperature sensors and compensation circuits to adjust the oscillator's frequency, counteracting temperature-induced deviations. Similarly, Oven-Controlled Crystal Oscillators (OCXOs) maintain the quartz crystal within a stable thermal environment, significantly reducing frequency fluctuations.

Recent advancements in simulation-based optimization have revolutionized the design and analysis of quartz oscillators. By employing tools like Finite Element Method (FEM) simulations, engineers can model the thermal and mechanical behaviors of oscillators under various conditions. This predictive capability allows for the identification of potential issues before physical prototypes are constructed, saving time and resources. Moreover, optimization algorithms enable the fine-tuning of design parameters to achieve desired performance metrics, such as low phase noise and high frequency stability. The integration of these advanced modeling and control techniques underscores the importance of system-level engineering in the development of stable quartz oscillators. By considering the oscillator's behavior within the broader system context, engineers can design more robust and reliable frequency sources, meeting the stringent requirements of modern electronic applications.

In summary, the field of control engineering has significantly contributed to the advancement of quartz oscillator technology. Through the application of comprehensive system design principles, temperature compensation methods, and simulation-based optimization, the performance of quartz oscillators has been enhanced, ensuring their continued relevance in precision applications.

V. APPLICATIONS AND FUTURE TRENDS

Ultra-stable quartz oscillators are vital in satellite navigation, radio astronomy, radar systems, and metrology. Emerging requirements, such as 5G networks and autonomous systems, push for compact, low-power, and ultra-stable sources.

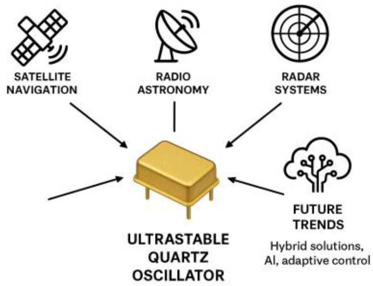

Fig. 5. Context of the future system integration control environment of the quartz oscillators development.

While optical clocks are advancing, quartz oscillators remain indispensable due to their maturity, cost-effectiveness, and proven reliability. As illustrated on Fig. 5, future efforts will likely focus on hybrid solutions combining quartz with novel stabilization techniques, leveraging artificial intelligence and adaptive control strategies.

V.1. Future trends

Ultra-stable quartz oscillators play a critical role in a wide array of high-precision systems, including satellite navigation, radio astronomy, radar systems, and metrology. In these applications, the oscillator’s stability directly impacts the accuracy of positioning, timing, and measurement, making them a backbone of modern technological infrastructure. Emerging technological demands—such as 5G and future 6G communication networks, autonomous vehicles, and next-generation aerospace systems—are driving the need for oscillators that are not only ultra-stable, but also compact, low-power, and resilient under diverse environmental conditions. These requirements are challenging traditional oscillator design, pushing toward innovations in miniaturization, thermal compensation, and vibration-insensitive architectures. The future development of quartz oscillators is increasingly oriented toward integrated system environments, where the oscillator interacts seamlessly with other subsystems in satellite navigation, radar, and radio astronomy. In such integrated systems, adaptive control mechanisms can dynamically compensate for environmental disturbances, ensuring consistent performance. Artificial intelligence (AI) and machine learning techniques are poised to play a role in predictive maintenance, real-time error correction, and optimization of oscillator performance within complex networks. Despite the rapid advancement of optical clocks, quartz oscillators remain indispensable in industry due to their mature technology, cost-effectiveness, and proven reliability. Figure 5 illustrates a likely trajectory for future developments: hybrid solutions that combine traditional quartz technology with novel stabilization methods, such as optical stabilization loops, temperature-compensated designs, and AI-driven adaptive control, where recent publications in this AI domain highlight how machine learning and advanced modeling approaches improve the performance and applicability of quartz-based oscillators and sensors. Kirimli et al. [16] demonstrate that machine learning can optimize impedance measurement parameters in quartz crystal microbalance (QCM) systems, thereby enhancing detection limits in biosensing. Su et al. [17] employ long short-term memory (LSTM) networks combined with transfer learning to accurately predict frequency deviations in crystal oscillators, addressing stability and reliability challenges. Muckley et al. [18] introduce a scalable, low-cost QCM array platform for environmental sensing, which provides a foundation for integrating data-driven methods to handle complex, large-scale sensing tasks. Finally, Deng et al. [19] refine the modeling of quartz resonator frequency–temperature behavior by incorporating thermal hysteresis, offering improved accuracy for oscillator performance prediction and compensation. Collectively, these works show that machine learning and enhanced modeling significantly improve sensitivity, prediction accuracy, scalability, and robustness in the quartz oscillator domain. These hybrid approaches aim to bridge the gap between ultra-high precision and practical deployment constraints, creating oscillators that can meet the stringent requirements of next-generation systems. In summary, the future of quartz oscillator technology lies in hybrid, intelligent, and highly integrated solutions, where conventional stability is enhanced through advanced control strategies, AI, and system-level optimization, ensuring that quartz oscillators remain a cornerstone of precision timing and navigation for decades to come.

V.2. Applications in Key Domains

In the context of satellite navigation, the push for ultra-stable, compact, and low-power oscillators is crucial for maintaining precise timing across large satellite constellations. Future hybrid solutions may integrate quartz oscillators with AI-driven stabilization, enabling real-time correction of drift caused by temperature fluctuations or radiation in space. This would ensure higher accuracy in global positioning systems and improve synchronization for critical services such as autonomous transport and global communication networks. For radar systems, especially in defense and air traffic control, oscillator stability translates directly into range resolution and target identification accuracy. The integration of adaptive control strategies allows quartz oscillators to dynamically adjust to vibration, shock, and environmental stress, maintaining radar performance in harsh or mobile environments. Future hybrid designs could couple quartz oscillators with optical references or MEMS-based sensors to achieve both ruggedness and ultra-high stability. In radio astronomy, where long-baseline interferometry relies on the synchronization of signals received across vast distances, oscillator stability is fundamental. Even small timing errors can lead to phase incoherence and loss of sensitivity in cosmic observations. The application of machine learning for adaptive control can provide real-time phase correction, while hybrid quartz–optical solutions may extend observation accuracy without significantly raising system costs. Do et al. [20] advance the field of low-power oscillator design by demonstrating a hybrid capacitive MEMS oscillator that combines the compactness and ruggedness of MEMS devices with frequency stability improvements typically associated with quartz, offering a pathway toward energy-efficient and miniaturized timing solutions for space and mobile applications. Su, Nguyen, and Chao [21] contribute to the emerging domain of AI-stabilized oscillators by applying long short-term memory (LSTM) networks with transfer learning to predict frequency deviations in crystal oscillators caused by thermal hysteresis, thus enabling proactive drift compensation and real-time correction strategies crucial for reliable satellite navigation and radar systems. Finally, Schuldt et al. [22] enrich the field of satellite navigation and timing by reviewing the maturity of optical clock technologies for GNSS, highlighting how compact optical references could complement or surpass microwave-based oscillators, thereby enhancing global positioning accuracy, synchronization robustness, and the long-term feasibility of integrating hybrid quartz–optical architectures into next-generation navigation constellations. Taken together, these trends suggest a convergence of quartz technology with hybrid stabilization, AI-enhanced control, and system-level integration, ensuring that oscillators continue to underpin next-generation navigation, sensing, and observational platforms while complementing emerging technologies such as optical clocks.

VI. Conclusion

Control science engineering has significantly advanced the performance of ultra-stable quartz oscillators. Through temperature control, drive-level optimization, and phase noise reduction, researchers have achieved remarkable improvements in frequency stability. The synergy between resonator physics and system-level control will continue to drive innovation, ensuring quartz oscillators remain a cornerstone of frequency control technology. The progress summarized in this work demonstrates that control methodologies are no longer auxiliary tools but rather central design elements in modern oscillator development. Precise modeling of nonlinear effects, careful management of thermal environments, and advanced signal processing techniques allow engineers to overcome long-standing physical limitations of quartz devices. By systematically combining these approaches, it has become possible to reach stability levels that were once considered unattainable for bulk acoustic wave resonators. Such achievements confirm the resilience of quartz technology in the face of competition from optical and atomic frequency standards, underscoring its importance for both established and emerging applications. Another critical outcome of these advances is the shift toward system-level engineering. Rather than optimizing resonators in isolation, current research emphasizes the integration of quartz oscillators within complex architectures such as satellite payloads, telecommunication infrastructures, or scientific instrumentation platforms. This holistic view ensures that stability enhancements are maintained under real operating conditions, where environmental fluctuations, power constraints, and long-term reliability are decisive factors. The convergence of material science, electronics, and control theory thus represents a multidisciplinary pathway to the next generation of frequency standards.

Looking ahead, the field is poised to benefit from the incorporation of artificial intelligence and machine learning methods, which can provide adaptive control, predictive diagnostics, and self-correction capabilities in real time. Such strategies are particularly relevant for future navigation systems, autonomous vehicles, and high-capacity communication networks, where timing precision and robustness must coexist with compactness and low energy consumption. Hybrid solutions, combining quartz oscillators with optical or MEMS-based stabilization techniques, are also expected to emerge, bridging the gap between the exceptional long-term stability of advanced frequency standards and the practical advantages of quartz technology.

In summary, control science engineering has elevated quartz oscillators from reliable components into highly optimized systems capable of meeting the most demanding requirements of modern technology. While new alternatives continue to develop, the enduring combination of maturity, cost-effectiveness, and performance ensures that quartz oscillators will remain indispensable for decades to come. Their sustained evolution, driven by innovation in control engineering, positions them as both a legacy technology and a forward-looking solution in the ongoing quest for precise, stable, and accessible frequency control.

REFERENCES

[1] P. Salzenstein, A. Kuna, L. Sojdr, and J. Chauvin, "Significant step in ultra high stability quartz crystal oscillators," Electronics Letters, vol. 46, no. 21, pp. 1433–1434, 2010. doi: 10.1049/el.2010.1828.

[2] J. R. Norton, J. M. Cloeren and P. G. Sulzer, "Brief history of the development of ultra-precise oscillators for ground and space applications," Proceedings of 1996 IEEE International Frequency Control Symposium, Honolulu, HI, USA, 1996, pp. 47-57, doi: 10.1109/FREQ.1996.559818.

[3] W. G. Cady, "The Piezo-Electric Resonator," in Proceedings of the Institute of Radio Engineers, vol. 10, no. 2, pp. 83-114, April 1922, doi: 10.1109/JRPROC.1922.219800.

[4] P. Salzenstein, "Frequency and temperature control for complex system engineering in optoelectronics and electronics: an overview," Int. J. for Simulation and Multidisciplinary Design Optimization, vol. 11, p. 7, 2020. doi: 10.1051/smdo/2020001.

[5] R. J. Besson, "A New "Electrodeless" Resonator Design," 31st Annual Symposium on Frequency Control, Atlantic City, NJ, USA, 1977, pp. 147-152, doi: 10.1109/FREQ.1977.200141.

[6] A. Clairet, L. Couteleau, T. Laroche and J.-J. Boy, "Experimental and theoretical results on SC-cut quartz resonators collectively realized on 4" wafers," 2013 Joint European Frequency and Time Forum & International Frequency Control Symposium (EFTF/IFC), Prague, Czech Republic, 2013, pp. 662-665, doi: 10.1109/EFTF-IFC.2013.6702210.

[7] Mihir S. Patel, Yook-Kong Yong and Masako Tanaka, "Drive level dependency in quartz resonators," International Journal of Solids and Structures, vol. 46, no. 9, pp. 1856-1871, 2009. doi: 10.1016/j.ijsolstr.2008.12.021.

[8] P. Salzenstein, F. Lefebvre, and M. Addouche, "Drive level dependence and origin of noise in ultra-stable piezoelectric crystal resonators," Proc. SPIE, vol. 13241, Optical Metrology and Inspection for Industrial Applications XI, p. 132411Y, 2024, doi: 10.1117/12.3036701.

[9] F. Sthal, M. Mourey, F. Marionnet, and W. F. Walls, "Phase noise measurements of 10 MHz BVA quartz crystal resonator," IEEE Trans. Ultrason. Ferroelectr. Freq. Control, vol. 47, no. 2, pp. 369–373, 2000. doi: 10.1109/58.827422.

[10] F. Sthal, J. Imbaud, X. Vacheret, P. Salzenstein, G. Cibiel, and S. Galliou, "Computation method for the short-term stability of quartz crystal resonators obtained from passive phase noise measures," IEEE Trans. Ultrason. Ferroelectr. Freq. Control, vol. 60, no. 7, pp. 1530–1532, 2013. doi: 10.1109/TUFFC.2013.2725.

[11] W. A. Marrison, "The evolution of the quartz crystal clock," Bell Syst. Tech. J., vol. 27, no. 3, pp. 510–588, 1948, doi: 10.1002/j.1538-7305.1948.tb01343.x.

[12] F. L. Walls, "The quest to understand and reduce 1/f noise in amplifiers and BAW quartz oscillators," in Proc. 9th Eur. Freq. Time Forum, Besançon, France, 1995, pp. 227–240.

[13] T. l. Carron and J. Leost, "FEM thermal analysis of quartz oscillator with COMSOL," 2009 IEEE International Frequency Control Symposium Joint with the 22nd European Frequency and Time forum, Besancon, France, 2009, pp. 482-486, doi: 10.1109/FREQ.2009.5168226.

[14] X. Deng, S. Wang, S. Jing, X. Huang, W. Huang and B. Cui, "Dynamic Frequency–Temperature Characteristic Modeling for Quartz Crystal Resonator Based on Improved Echo State Network," in IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 69, no. 1, pp. 438-446, Jan. 2022, doi: 10.1109/TUFFC.2021.3118929.

[15] S. Galliou and M. Mourey, "Temperature processing of an ultra stable quartz oscillator," in IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 48, no. 6, pp. 1539-1546, Nov. 2001, doi: 10.1109/58.971705.

[16] K. E. Kirimli, E. -Elgun, and U. Unal, "Machine learning approach to optimization of parameters for impedance measurements of Quartz Crystal Microbalance to improve limit of detection," Biosensors and Bioelectronics: X, vol. 10, p. 100121, 2022, doi: 10.1016/j.biosx.2022.100121.

[17] B.-C. Su, D. Nguyen, and P.-P. Chao, "Predicting frequency deviation of a crystal oscillator based on long short-term memory network and transfer learning technique," Microsystem Technologies, vol. 31, pp. 1175–1189, 2025, doi: 10.1007/s00542-024-05691-2.

[18] E. S. Muckley, C. Anazagasty, C. B. Jacobs, T. Hianik, and I. N. Ivanov, "Low-cost scalable quartz crystal microbalance array for environmental sensing," Proc. SPIE, vol. 9944, Organic Sensors and Bioelectronics IX, 2016, Art. no. 99440Y, doi: 10.1117/12.2237942.

[19] X. Deng, S. Wang, X. Huang, H. Liu and B. Cui, "Modified Modeling Method of Quartz Crystal Resonator Frequency–Temperature Characteristic with Considering Thermal Hysteresis," in IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 68, no. 3, pp. 890-898, March 2021, doi: 10.1109/TUFFC.2020.3014887.

[20] C. Do, A. Erbes, J. Yan, and A. A. Seshia, "Design and implementation of a low-power hybrid capacitive MEMS oscillator," Microelectronics Journal, vol. 56, pp. 1–9, Oct. 2016. doi: 10.1016/j.mejo.2016.07.007.

[21] B.-C. Su, D. H. Nguyen, and P. C.-P. Chao, "Predicting frequency deviation of a crystal oscillator based on long short-term memory network and transfer learning technique," Microsystem Technologies, 2024. doi: 10.1007/s00542-024-05691-2.

[22] T. Schuldt et al., "Optical clock technologies for global navigation satellite systems," GPS Solutions, vol. 25, art. no. 83, Apr. 2021. doi: 10.1007/s10291-021-01113-2.