

A review on Structural Optimization and Dynamic Behaviour of Telecommunication Equipment Mounting Brackets

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Abstract- Telecommunication infrastructure has expanded rapidly with the deployment of advanced wireless technologies, placing increased emphasis on the structural reliability of equipment support systems. Telecommunication equipment mounting brackets, though relatively small in size, play a critical role in ensuring load transfer, positional stability, and long-term serviceability of antennas, radio units, and associated hardware installed on towers, poles, and building façades. These brackets are continuously exposed to complex dynamic environmental loads, including wind-induced forces, vibration, and seismic excitation, which can lead to excessive deformation, resonance, fatigue damage, and, in severe cases, structural failure. Conventional bracket designs often rely on conservative safety factors, resulting in overdesigned structures with increased weight and cost, while still remaining vulnerable to dynamic loading effects. This review paper presents a comprehensive synthesis of existing research on the structural optimization and dynamic behaviour of telecommunication equipment mounting brackets. The review examines functional and environmental requirements, material selection, dynamic loading conditions, and numerical modelling approaches, with particular emphasis on finite element analysis as a primary tool for evaluating structural and vibration response. Modal analysis, harmonic and random vibration analysis, and seismic response evaluation are discussed to highlight their roles in understanding resonance susceptibility and fatigue behaviour. Furthermore, the paper reviews optimization philosophies and techniques aimed at achieving lightweight, durable, and vibration-resistant bracket designs. By consolidating findings from telecom-specific studies and related engineering domains, this review identifies key research gaps and outlines future directions for developing robust and resilient mounting systems capable of meeting the demands of modern telecommunication infrastructure.

Keywords- Telecommunication mounting brackets; Structural optimization; Dynamic behaviour; Finite element analysis; Vibration and seismic loading; Fatigue durability

I. INTRODUCTION

The rapid expansion of telecommunication networks, driven by the proliferation of mobile communication, broadband internet, and emerging technologies such as fifth-generation systems and the Internet of Things, has significantly increased the demand for reliable and resilient infrastructure. Telecommunication equipment including antennas, remote radio units, baseband units, power supply modules, and fiber distribution systems is typically installed at elevated locations on towers, poles, rooftops, and building façades to ensure wide-area coverage and signal quality [1]. The mechanical stability and long-term functionality of these systems are largely dependent on telecommunication equipment mounting brackets, which serve as the primary interface between the equipment and the supporting structure [2].

Telecommunication equipment mounting brackets are critical structural components designed to ensure positional stability, effective load transfer, and precise alignment of mounted equipment under service conditions. These brackets must securely anchor telecom devices while maintaining structural integrity throughout their operational life [3]. Failure of mounting brackets can result in equipment damage, service disruption, and potential safety hazards, underscoring their importance within modern communication infrastructure. Despite their relatively compact size, mounting brackets play a decisive role in the overall reliability and safety of telecom installations [4].

In service environments, telecom mounting brackets are continuously subjected to complex dynamic environmental loads. Wind pressure acts persistently on exposed equipment surfaces, inducing both static and fluctuating stresses in the supporting brackets. Vibrations arise from wind-induced oscillations, tower sway, operational equipment activity, and external sources such as traffic or nearby machinery. In seismically active regions, earthquake-induced ground motion introduces sudden inertial forces that can cause excessive deformation or even structural failure if the bracket design is inadequate. These loads are multi-directional, time-dependent, and often act simultaneously, making the structural behaviour of mounting brackets highly complex [5].

Conventional mounting bracket designs commonly rely on conservative safety factors to account for these uncertainties. While such approaches may satisfy basic strength requirements, they often lead to excessive material usage, increased weight, and higher manufacturing and installation costs. Moreover, overdesigned

brackets may still be susceptible to fatigue damage due to stress concentration, resonance, and long-term vibration exposure. The study strongly emphasizes the need for optimized bracket designs that can efficiently resist deformation, minimize stress concentration, and enhance fatigue durability under real-world dynamic loading conditions [6].

Structural optimization, supported by advanced numerical techniques such as finite element analysis, has therefore emerged as a critical approach for improving the efficiency and reliability of telecommunication mounting brackets. Optimization strategies aim to achieve an optimal balance between strength, stiffness, weight reduction, and durability, while ensuring compliance with safety and performance requirements [7]. Alongside optimization, a thorough understanding of the dynamic behaviour of mounting brackets under wind, vibration, and seismic excitation is essential to prevent resonance, reduce fatigue damage, and ensure long-term serviceability [8].

Accordingly, this review paper presents a comprehensive synstudy of existing research on the structural optimization and dynamic behaviour of telecommunication equipment mounting brackets. The review consolidates findings from telecom-specific studies as well as related research in automotive, railway, aerospace, and structural engineering domains where similar bracket systems have been extensively investigated. Emphasis is placed on design requirements, dynamic loading conditions, finite element modelling approaches, vibration and seismic analysis techniques, optimization methodologies, and observed failure mechanisms. The objective is to establish a unified understanding of current research trends, identify gaps specific to telecom infrastructure, and outline future directions for the development of robust, efficient, and resilient telecommunication mounting systems.

II. TELECOMMUNICATION EQUIPMENT MOUNTING BRACKETS AND THEIR FUNCTIONAL REQUIREMENTS

Telecommunication equipment mounting brackets function as intermediary structural components that transfer loads from mounted equipment to the primary supporting structures such as towers, poles, and building façades. These brackets are required to accommodate a wide range of equipment geometries, weights, and installation orientations, including pole-mounted, tower-mounted, and rooftop-mounted configurations. Each installation scenario introduces distinct mechanical and environmental constraints, making the design of mounting brackets a critical aspect of telecom infrastructure reliability [9]. From a functional perspective, mounting brackets must provide sufficient stiffness to maintain accurate equipment alignment while allowing limited flexibility to absorb dynamic loads. Excessive deformation can lead to misalignment of antennas or radio units, adversely affecting signal quality, coverage efficiency, and operational lifespan of telecom components. At the same time, brackets must ensure effective load-bearing capacity under combined static and dynamic forces without inducing localized stress concentrations that may accelerate fatigue failure [10].

Environmental durability further defines the functional requirements of telecom mounting brackets. These components operate in outdoor environments and are exposed to temperature variations, humidity, ultraviolet radiation, and corrosive conditions. Consequently, long-term resistance to corrosion and material degradation is essential. Safety considerations also demand that mounting brackets retain structural integrity during extreme events such as storms or earthquakes, preventing equipment detachment and associated hazards. The combination of structural performance, environmental resilience, and operational functionality makes telecom mounting brackets complex engineering components rather than simple support elements, thereby necessitating systematic analysis and optimization strategies.

III. MATERIALS USED IN TELECOMMUNICATION MOUNTING BRACKETS

Material selection plays a decisive role in determining the structural performance and dynamic behaviour of telecommunication mounting brackets. High-strength structural steels are widely used due to their favorable mechanical properties, availability, and cost-effectiveness. Galvanized steel is commonly adopted to enhance corrosion resistance in outdoor environments, particularly in coastal or industrial regions. The high stiffness of steel brackets contributes to reduced deformation under load, which is essential for maintaining equipment alignment [11].

Aluminium alloys have also gained attention as alternative materials due to their lower density and good corrosion resistance. Aluminium brackets offer significant weight reduction benefits, which can simplify installation and reduce loads on supporting structures. However, the lower modulus of elasticity of aluminium compared to steel

can lead to increased deformation and altered vibration characteristics, necessitating careful design considerations [12]. Emerging materials such as fiber-reinforced polymer composites and hybrid metal–composite systems have been explored in limited studies. These materials offer high strength-to-weight ratios and excellent corrosion resistance, but their higher cost, manufacturing complexity, and limited long-term field data have constrained widespread adoption in telecom applications [13].

The dynamic response of mounting brackets is strongly influenced by material properties such as density, elastic modulus, damping capacity, and fatigue resistance. Materials with higher inherent damping can reduce vibration amplitudes, thereby enhancing fatigue life. Consequently, material selection must balance static strength, dynamic performance, durability, and economic considerations [14].

IV. DYNAMIC LOADING CONDITIONS ACTING ON TELECOMMUNICATION MOUNTING BRACKETS

The dynamic behaviour of telecommunication equipment mounting brackets is a critical aspect of their structural reliability, as these components are continuously exposed to time-varying environmental and operational loads. The study emphasizes that understanding dynamic response characteristics is essential for preventing resonance, limiting excessive deformation, and enhancing fatigue durability under real-world service conditions. Dynamic behaviour is primarily investigated through modal analysis, vibration response evaluation, and seismic response assessment, each contributing to a comprehensive understanding of bracket performance under multi-hazard loading scenarios.

A. Modal Characteristics and Natural Frequency Behaviour

Modal analysis is highlighted in the study as a fundamental step in characterizing the dynamic behaviour of telecom mounting brackets. Determination of natural frequencies and mode shapes provides essential insight into how brackets respond to dynamic excitation. The study discusses that modal characteristics are strongly influenced by factors such as mass distribution of the mounted equipment, stiffness of the bracket geometry, material properties, and mounting configuration. Variations in orientation, such as vertical or horizontal installation, can significantly alter dominant vibration modes and associated natural frequencies [15].

Avoidance of resonance between the natural frequencies of the bracket–equipment system and operational or environmental excitation frequencies is identified as a critical design requirement. Resonant conditions can lead to amplified vibration amplitudes, elevated stress levels, and accelerated fatigue damage. Consequently, modal analysis serves as a guiding tool for design refinement, enabling modification of geometry or stiffness to shift natural frequencies away from critical excitation ranges and improve long-term structural reliability [16].

B. Harmonic and Random Vibration Response

The study reviews harmonic response analysis as an effective method for evaluating steady-state vibration behaviour of mounting brackets subjected to sinusoidal excitation. Harmonic analysis allows identification of resonance zones and quantification of peak stress and displacement responses at specific excitation frequencies. Frequency response characteristics obtained through this approach are particularly useful for assessing the susceptibility of brackets to periodic loads induced by wind fluctuations or operational equipment vibrations [17]. In addition to harmonic excitation, the study highlights random vibration analysis as a more realistic representation of actual service conditions. Random excitation sources such as wind turbulence, tower sway, and ground-borne vibrations are inherently unpredictable and cannot be adequately described using deterministic loading alone. Power spectral density–based methods are employed to characterize these stochastic inputs and evaluate statistical response measures, including root mean square stress and displacement. These measures are crucial for fatigue assessment, as they provide insight into cumulative damage potential under prolonged vibration exposure. The combined use of harmonic and random vibration analyses enables a more comprehensive evaluation of vibration-induced risks in telecom mounting brackets [18].

C. Seismic Response and Earthquake Considerations

Earthquake-induced loading is treated in the study as a critical extreme event that can significantly affect telecommunication mounting brackets, particularly in seismically active regions. Seismic ground motion generates inertial forces proportional to the mass of the mounted equipment, which are transmitted through the bracket to the supporting structure. If not adequately considered during design, these forces can result in excessive deformation, high stress concentration, or structural failure [19].

The study employs response spectrum analysis to estimate peak structural response under seismic excitation. This approach enables evaluation of maximum expected stresses and displacements based on the dynamic properties

of the bracket system and prescribed seismic spectra. The findings emphasize that seismic loads can govern design requirements in certain regions and must be integrated alongside wind and vibration considerations. Ensuring seismic resilience of telecommunication mounting brackets is therefore essential for maintaining uninterrupted communication services during and after earthquake events, reinforcing the importance of dynamic analysis in robust bracket design [20].

V. FINITE ELEMENT MODELLING APPROACHES FOR MOUNTING BRACKETS

Finite Element Analysis has been extensively employed in the study as the primary computational framework for evaluating the structural and dynamic response of telecommunication equipment mounting brackets. Owing to the complex geometry of bracket assemblies and the multi-hazard loading environment in which they operate, analytical solutions are often impractical. FEA provides a robust numerical approach to predict stress distribution, deformation patterns, and vibration characteristics under various loading scenarios, including wind, harmonic excitation, random vibration, and seismic effects. The ability of FEA to simulate realistic operating conditions without the need for physical prototypes makes it particularly suitable for iterative design assessment and structural optimization in telecom infrastructure applications [21].

Through finite element simulations, critical regions prone to high stress concentration and excessive deformation can be identified at early stages of the design process. This facilitates informed design modifications aimed at improving load distribution, enhancing stiffness, and reducing the likelihood of fatigue damage. Furthermore, FEA-based modal analysis enables the determination of natural frequencies and mode shapes, which are essential for assessing resonance susceptibility and guiding vibration-resistant design strategies [22].

Accurate geometric modelling, appropriate mesh density, and realistic representation of boundary conditions are emphasized in the study as essential prerequisites for reliable numerical predictions. The interaction between the mounting bracket and the supporting structure, such as the bracket-pole interface, significantly influences the global stiffness and dynamic response of the system. Similarly, bolted connections and contact interfaces must be carefully modelled to capture load transfer mechanisms and local stress behaviour. Representation of the mounted equipment mass is equally important, as it directly affects inertial forces and modal characteristics [23].

Material properties and contact definitions play a critical role in ensuring that simulation outcomes closely reflect real-world behaviour. Proper assignment of elastic properties, density, and damping parameters allows for realistic estimation of structural response under dynamic loading. The study highlights that inadequately defined boundary conditions or coarse meshing can lead to erroneous stress predictions and misleading conclusions. Consequently, mesh convergence studies and validation against established analytical or experimental benchmarks are necessary to enhance the credibility of FEA results [24].

Overall, the application of finite element analysis, as presented in the study, forms the foundation for understanding the structural integrity and dynamic behaviour of telecommunication equipment mounting brackets. When integrated with structural optimization techniques, FEA serves as a powerful tool for developing lightweight, durable, and vibration-resistant bracket designs capable of withstanding real-world environmental loading conditions.

VI. STRUCTURAL OPTIMIZATION PHILOSOPHY FOR TELECOM MOUNTING BRACKETS

Structural optimization of telecommunication equipment mounting brackets is presented in the study as a key strategy to enhance structural efficiency while maintaining safety and reliability. Conventional bracket designs often employ conservative safety factors to account for uncertainties associated with dynamic environmental loading. While such designs satisfy basic strength requirements, they frequently result in excessive material usage, increased weight, and higher manufacturing, transportation, and installation costs [25]. Structural optimization addresses these limitations by enabling weight reduction and improved load distribution without compromising structural integrity. Lightweight optimized brackets reduce the overall load transmitted to towers and poles, thereby improving the stability of supporting structures and simplifying installation and maintenance activities. Reduced material usage directly contributes to lower fabrication costs and improved economic efficiency, which is particularly important in large-scale telecom deployment projects. In addition to weight reduction, optimization plays a critical role in minimizing stress concentrations, which are primary contributors to fatigue failure under cyclic wind, vibration, and seismic loading conditions [26].

The study outlines several key objectives guiding the optimization of telecom mounting brackets. These include achieving adequate stiffness to limit deformation and maintain equipment alignment, ensuring sufficient strength to prevent yielding under extreme loading conditions, and enhancing vibration resistance to avoid resonance and associated fatigue damage. Optimization efforts also emphasize the importance of material selection, geometric configuration, and manufacturability. The choice of material influences stiffness, damping, and fatigue resistance, while geometric refinement enables efficient load paths and reduced stress concentration. Manufacturability constraints must be considered to ensure that optimized designs can be practically fabricated and deployed. Overall, the optimization philosophy discussed in the study is centered on achieving a balanced design that integrates structural efficiency with long-term durability. Rather than focusing solely on weight reduction, effective optimization seeks to improve dynamic behaviour, fatigue resistance, and service reliability of telecom mounting brackets under real-world environmental loading conditions [27].

VII. CONCLUSION

This review has highlighted that telecommunication equipment mounting brackets are critical structural components whose reliability directly affects the safety and performance of modern communication infrastructure. The synthesis of existing studies demonstrates that dynamic environmental loads, particularly wind, vibration, and seismic excitation, govern bracket behaviour more significantly than static loads alone. Finite element analysis has emerged as an indispensable tool for evaluating stress distribution, deformation, modal characteristics, and vibration response, while structural optimization offers effective pathways for reducing weight, minimizing stress concentration, and improving fatigue resistance without compromising safety.

Despite notable progress, several research gaps remain. Future studies should focus on integrated multi-hazard analysis frameworks that simultaneously consider wind, vibration, and seismic effects, along with long-term fatigue behaviour under realistic service conditions. Experimental validation, field monitoring, and life-cycle performance assessment of optimized bracket designs remain limited and warrant further investigation. The incorporation of advanced materials, data-driven optimization techniques, and digital-twin-based monitoring systems represents a promising direction for enhancing the durability, resilience, and cost efficiency of telecommunication mounting brackets in next-generation infrastructure.

References

- [1] Hounghonon, G. V., Ivaldi, M., Palikot, E., & Strusani, D. (2025). The impact of shared telecom infrastructure on digital connectivity and inclusion. *arXiv preprint arXiv:2507.19693*.
- [2] Jiang, W., Wang, K. L., & Miao, Z. (2025). Can telecommunications infrastructure enhance urban resilience? Empirical evidence from a differences-in-differences approach in China. *Environment, Development and Sustainability*, 27(1), 2379-2410. <https://doi.org/10.1007/s10668-023-03971-x>
- [3] Gaver, W., & Gaver, F. (2023, April). Living with light touch: An autoethnography of a simple communication device in long-term use. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (pp. 1-14). <https://dl.acm.org/doi/10.1145/3544548.3580807>
- [4] Shatov, V., Nuss, B., Schieler, S., Bishoyi, P. K., Wimmer, L., Luebke, M., ... & Franchi, N. (2024). Joint radar and communications: Architectures, use cases, aspects of radio access, signal processing, and hardware. *IEEE Access*, 12, 47888-47914. Digital Object Identifier 10.1109/ACCESS.2024.3383771
- [5] Zhang, H., Shi, W., Chen, Z., Feng, G., & He, B. (2023). Effect of mounting bracket structure and material on automotive air conditioning compressor. *Australian Journal of Mechanical Engineering*, 21(1), 179-191. <https://doi.org/10.1080/14484846.2020.1838751>
- [6] Bildirici, D., Topaç, M. M., Polat, K. İ. N. Y. A. S., Zavrak, T., & Arman, Y. (2024). Failure analysis-based mass reduction of an aluminium alloy engine mounting bracket using Design of Experiments approach. *Engineering Failure Analysis*, 166, 108927. <https://doi.org/10.1016/j.engfailanal.2024.108927>
- [7] Huang, Z., Wang, Z., Feng, J., & Shi, X. (2024, October). Research on Structural Optimization of Support Bracket Under Complex Static and Dynamic Environment. In *2024 5th International Conference on Intelligent Design (ICID)* (pp. 348-352). IEEE. <https://doi.org/10.1109/ICID64166.2024.11024898>

- [8] Jornet, J. M., Petrov, V., Wang, H., Popovic, Z., Shakya, D., Siles, J. V., & Rappaport, T. S. (2024). The evolution of applications, hardware design, and channel modeling for terahertz (THz) band communications and sensing: Ready for 6G?. *arXiv preprint arXiv:2406.06105*.
- [9] Szmeja, P., Fornés-Leal, A., Lacalle, I., Palau, C. E., Ganzha, M., Pawłowski, W., ... & Schabbink, J. (2023). ASSIST-IoT: A modular implementation of a reference architecture for the next generation Internet of Things. *Electronics*, 12(4), 854. <https://doi.org/10.3390/electronics12040854>
- [10] Wild, T., Grudnitsky, A., Mandelli, S., Henninger, M., Guan, J., & Schaich, F. (2023, September). 6G integrated sensing and communication: From vision to realization. In *2023 20th European Radar Conference (EuRAD)* (pp. 355-358). IEEE. <https://doi.org/10.23919/EuRAD58043.2023.10289474>
- [11] Rangaiah, P. K., Engstrand, J., Johansson, T., Perez, M. D., & Augustine, R. (2023). 92 Mb/s fat-intrabody communication (fat-IBC) with low-cost WLAN hardware. *IEEE Transactions on Biomedical Engineering*, 71(1), 89-96. Digital Object Identifier 10.1109/TBME.2023.3292405
- [12] Liu, L., Wang, D., Wang, D., Sun, Y., Lin, H., Gong, X., ... & Liu, M. (2024). Domain wall magnetic tunnel junction-based artificial synapses and neurons for all-spin neuromorphic hardware. *Nature Communications*, 15(1), 4534. <https://doi.org/10.1038/s41467-024-48631-4>
- [13] Ezzat, M., Maged, M., Gamal, Y., Adel, M., Alrahmawy, M., & El-Metwally, S. (2023). Blink-To-Live eye-based communication system for users with speech impairments. *Scientific Reports*, 13(1), 7961. <https://doi.org/10.1038/s41598-023-34310-9>
- [14] Gaikwad, N. B., Khare, S. K., Ugale, H., Mendhe, D., Tiwari, V., Bajaj, V., & Keskar, A. G. (2023). Hardware Design and Implementation of Multiagent MLP Regression for the Estimation of Gunshot Direction on IoBT Edge Gateway. *IEEE Sensors Journal*, 23(13), 14549-14557. <https://doi.org/10.1109/JSEN.2023.3278748>
- [15] Alkharisi, M. K., Alturki, M., & Raza, A. (2024). Predicting the various modal parameters of reinforced concrete beams for different near surface mounting sensor arrangements. *Results in Engineering*, 21, 101860. <https://doi.org/10.1016/j.rineng.2024.101860>
- [16] Criollo, L., Mena-Arciniega, C., Brazalez, J., Medina, F., & Zurita, M. (2025). Modal and random vibration analysis for structural design of aircraft external stores. *Aviation*, 29(3), 137-149. <https://doi.org/10.3846/aviation.2025.24456>
- [17] Li, X. Q., Pang, J., Yang, L., Jia, X. L., Lu, G., Yin, Z. H., & Shangguan, W. B. (2024). Finite Element Model refinement of powertrain mount brackets for estimating natural frequencies. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 238(1), 32-45. <https://doi.org/10.1177/09544070221127124>
- [18] Shen, S., Wang, Z., Pan, Y., & Yang, J. (2025). Analysis of dynamic response characteristics of landing impact for a certain type of turboprop engine under coupled connection mode of fuselage-support frame-vibration isolator-engine system. *European Journal of Mechanics-A/Solids*, 105937. <https://doi.org/10.1016/j.euromechsol.2025.105937>
- [19] Li, B., Guo, E., Sun, G., Ji, S., Mao, C., Wang, T., ... & Li, X. (2024). Shaking table test study on performance and functionality of a typical telecommunication room after earthquakes. *Earthquake Engineering and Engineering Vibration*, 23(2), 455-474. <https://doi.org/10.1002/eqe.3239>
- [20] Li, M., Niemeijer, A. R., & van Dinther, Y. (2025). Frictional healing and induced earthquakes on conventionally stable faults. *Nature Communications*, 16(1), 9140. <https://doi.org/10.1038/s41467-025-63482-3>
- [21] Ali, F. A., Hamandi, S. J., & Mohammed-Salih, H. S. (2025). Introducing a novel orthodontic bracket holder with a solidworks-based semiautomatic positioner tested via finite element analysis. *Discover Applied Sciences*, 7(3), 153. <https://doi.org/10.1007/s42452-024-06368-1>
- [22] Szafran, J., Juszczak-Andrasyk, K., & Kaszubska, P. (2025). Effectiveness Analysis of the Non-Standard Reinforcement of Lattice Tower Legs Using the Component-Based Finite Element Method. *Materials*, 18(6), 1242. <https://doi.org/10.3390/ma18061242>
- [23] Ayub, A., & Alhasyimi, A. A. (2025). Three-Dimensional Finite-Element Study into the Biomechanical Comparison of Force Distribution in Self-Ligating and Conventional Brackets. *Odovtos-International Journal of Dental Sciences*, (00), 403-417. <https://doi.org/10.15517/s9vbey74>

- [24] Li, J., Zhao, W., Li, C., Zhang, X., Deng, T., Wang, J., & Peng, J. (2025). An efficient parallel mesh generation method for finite element based analysis of large complex architecture. *Computer-Aided Design*, 182, 103851. <https://doi.org/10.1016/j.cad.2025.103851>
- [25] Ogunniran, A. O., Olusesan, O. O., Salako, J. T., Edet, A. I., Oyelami, E. O., Akadiri, O. O., & Jimoh, A. A. (2025). Metamaterials and smart structures: Leveraging AI for design, optimization and adaptive engineering solutions. *Global Journal of Engineering and Technology Advances*, 24(03), 115-139. <https://doi.org/10.30574/gjeta.2025.24.3.0260>
- [26] Jung, I., Peng, Z., & Rahmat-Samii, Y. (2024). Recent advances in reconfigurable electromagnetic surfaces: Engineering design, full-wave analysis, and large-scale optimization. *Electromagnetic Science*, 2(3), 1-25. <https://doi.org/10.23919/emsci.2024.0020>
- [27] Kabashkin, I., Perekrestov, V., Tyncherov, T., Shoshin, L., & Susanin, V. (2024). Framework for integration of health monitoring systems in life cycle management for aviation sustainability and cost efficiency. *Sustainability*, 16(14), 6154. <https://doi.org/10.3390/su16146154>

