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Feasibility Study of Powering Aircraft Landing Gear Sensors by Energy Harvesting Methods

Ruchi Jha[1], Rafael Luterbacher Mus[1], Rebecca Rodeck[1], Gerko Wende[1]
[1]German Aerospace Center (DLR), Institute of Maintenance, Repair and Overhaul
Hein-Saß-Weg 22, 21129 Hamburg, Germany
Ruchi.Jha@dlr.de; Rafael.LuterbacherMus@dlr.de; Rebecca.Rodeck@dlr.de; Gerko.Wende@dlr.de

Abstract –*This study investigates the feasibility of integrating energy-harvesting-powered wireless sensor systems within the landing gear of a Cessna Citation Jet (Model 525). The landing gear environment is characterised by broadband vibration during taxiing, high rotational energy during ground roll, and significant thermal dissipation during braking. Three complementary harvesting mechanisms- (1) piezoelectric vibration harvesting, (2) rotational harvesting from wheel motion, and (3) thermoelectric harvesting from brake heat, are evaluated using aircraft maintenance manual data and time-domain mission simulations. Harvested power profiles are integrated over representative taxi, take-off, landing, and post-landing phases to estimate the total recoverable electrical energy. The results demonstrate that approximately 155 Wh can be harvested over a representative operating cycle, with taxi operations providing the largest cumulative energy contribution and landing representing the highest instantaneous harvesting opportunity. The available energy is subsequently mapped to representative non-essential sensing applications, including structural health monitoring, tyre pressure monitoring, brake monitoring, and event logging. The analysis identifies maintenance-oriented, non-safety-critical monitoring functions as the most suitable candidates for early deployment. The proposed framework provides a quantitative basis for assessing the feasibility of subsystem-level energy harvesting in future more-electric aircraft while also supporting the retrofit of existing aircraft platforms.*

***Keywords*:** Energy harvesting, wireless technologies, Aircraft Landing Gear.

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1. Introduction

The aircraft landing gear is a critical subsystem responsible for supporting the aircraft during ground operations, absorbing landing impact loads, enabling braking, and facilitating steering. It must withstand significant static, dynamic and environmental stresses to ensure safe operation throughout taxi, takeoff, and landing phases [1], [2]. Landing gear systems incorporate multiple sensors, including tire pressure monitoring systems (TPMS), brake temperature sensors, weight-on-wheels (WOW) sensors, strut load and extension sensors, vibration sensors, and gear position indicators [3]. These sensors support condition-based maintenance and operational monitoring.

Conventional implementations rely on wired harnesses or battery-powered devices. Wiring increases mass and installation complexity, while batteries impose maintenance burdens and lifecycle management constraints [4]. Wireless sensor concepts remain limited by the need for reliable onboard power. Energy harvesting (EH) offers a potential alternative by converting ambient mechanical, thermal, or kinetic energy into electrical power, enabling lightweight and potentially self-sustaining sensor systems [5]. Although EH has been explored in structural health monitoring and aerospace applications [6], most transportation-focused studies address non-aerospace environments such as automotive and railway systems, where operational conditions differ substantially [7], [8]. Furthermore, existing work often evaluates individual harvesting mechanisms rather than providing a mission-level, system-oriented assessment [6]. Research

specifically addressing landing gear energy harvesting remains limited and largely conceptual [9], [10].

This paper presents a simulation-based feasibility study of integrated energy harvesting at the landing gear of a Cessna Citation Jet (Model 525). The main contributions are:

1. Quantitative mapping of sensor power requirements to three harvesting mechanisms-piezoelectric vibration, rotational kinetic, and thermoelectric brake heat.
2. Mission-phase feasibility assessment, integrating harvested power over taxi, takeoff, and landing to evaluate energy availability for representative sensor systems.

2. Methodology

This section describes the systematic selection of energy harvesting mechanisms, operational phase modeling, and sensor use-case definition for landing gear integration. The methodology establishes a structured framework for evaluating phase-dependent energy availability and practical implementation feasibility.

2.1 Selection of Energy Harvesting Mechanisms for Landing Gear Integration

The landing gear subsystem presents a structurally isolated yet energetically significant environment within the aircraft architecture. During taxi, takeoff, and landing operations, the gear is exposed to broadband mechanical vibrations, high rotational kinetic energy at the wheel assemblies, and substantial thermal dissipation within the braking system. Based on these characteristics, three complementary energy harvesting mechanisms were selected.

1. **Rotational Electromagnetic Harvesting –** This method utilizes wheel motion during taxi, takeoff roll, and landing rollout, where wheel angular velocity is proportional to ground speed. Electromagnetic generators can extract a small fraction of rotational mechanical power without affecting anti-skid control or braking performance, provided the harvested power remains a minor portion of available mechanical energy [9], [11].
2. **Piezoelectric Vibration Harvesting -** Piezoelectric harvesting exploits structural vibrations generated by runway irregularities, touchdown loads, and rolling friction in landing gear components. Piezoelectric transducers operate effectively at low-frequency excitation typical of landing gear dynamics (≈5–20 Hz) and can be mounted as thin patches on structural members without moving parts or interference with certified load paths, providing continuous low-power generation during taxi and landing phases [12]– [14].
3. **Thermoelectric Brake Harvesting -** Thermoelectric harvesting utilizes heat dissipated in brake assemblies during landing, where a significant portion of aircraft kinetic energy is converted into thermal energy within the braking system. Thermoelectric generators convert these temperature gradients into electrical power via the Seebeck effect, making this mechanism particularly suitable for capturing high transient energy during braking events [10], [15].

2.2 Operational Flight Phases Considered

Energy availability in the landing gear subsystem varies across ground operational phases, namely taxiing, takeoff roll, and landing roll. These phases differ in wheel rotational speed, vibration levels, thermal generation, and duration, with representative values based on operational profiles for light business jets [16].

2.3 Sensor Systems Considered as Use Cases

Four representative landing gear sensor systems were selected to evaluate the feasibility of energy-harvested wireless deployment:

1. **Landing Gear Health Monitoring** - This system incorporates accelerometers and strain sensors mounted on the strut or supporting structure to detect excessive vibration, fatigue, or hard landing events. Power demand is as low as 5-10 watts and continuous for sensing, with intermittent transmission during detected events [17].

2. **Brake and Thermal Monitoring** - Brake temperature sensors and wear indicators monitor thermal loading and component degradation. These systems operate primarily during and after landing, aligning well with thermoelectric harvesting availability [15].
3. **Wheel and Tire Monitoring (TPMS)** - Tire pressure monitoring systems measure pressure and temperature within the wheel assembly. Sensing power demand is around 3–6 W, though wireless transmission increases consumption. Rotational harvesting is well suited to this application [18].
4. **Edge Data Acquisition / Event Recorder** – This system logs landing loads and impact metrics locally and transmits data post-flight. Power demand is moderate and strongly duty-cycle dependent, making it compatible with combined harvesting mechanisms [19].

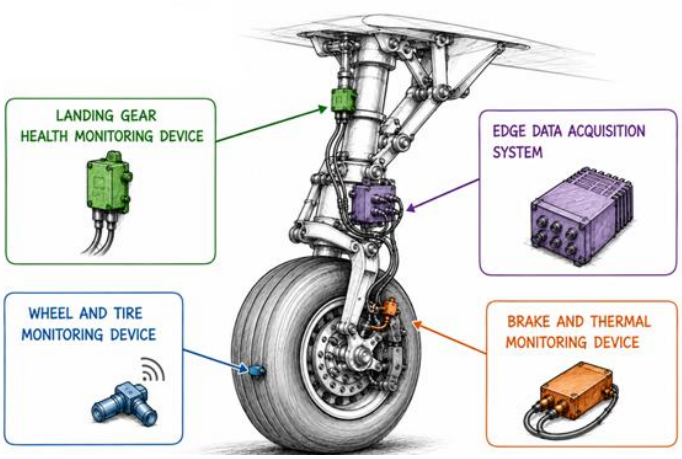

Figure 1. Schematic representation of energy harvesting opportunities within an aircraft landing gear system

Figure 1 shows a schematic representation of the harvesting opportunities and the potential applications for non-safety critical applications.

2.4 Mathematical Formulation and Model Development

A physics-based time-domain model was developed to estimate recoverable electrical power from landing gear subsystems during a representative flight mission cycle. The model considers three independent energy harvesting mechanisms:

1. Rotational energy extraction from the main landing gear wheels,
2. Piezoelectric harvesting from structural deformation and impact loading,
3. Thermoelectric harvesting from brake heat dissipation during landing.

The simulation is performed over a complete operational profile including idle, taxi, takeoff acceleration, flight, landing roll, and post-landing taxi phases and manufacture notes from the Cessna Citation Jet (Model 525) is used for data (refer to Table 1). The flight phases (climb, cruise, and descent) were not considered in this study due to the variability in flight envelope conditions and operating parameters across these regimes, which makes consistent energy harvesting modelling challenging.

Table 1.Summary of parameters for Cessna Citation 525 Jet (Model configuration)

Parameter	Symbol	Value	Assumption Type
Aircraft mass	m	7500 kg	Representative Landing mass
Gravitational acceleration	g	9.81 m/s^2	Standard
Wheel radius	r_w	0.30m	Typical light jet wheel
Number of main struts	n_{struts}	2	Twin main gear

The static load per strut is:

$$F_{wheel} = \frac{m \cdot g}{n_{struts}} \quad (1)$$

2.4.1 Rotational Energy Harvesting

Wheel angular velocity is given as [20]:

$$\omega(t) = \frac{v(t)}{r_w} \quad (2)$$

A taxi speed of 15 km/h and for acceleration and braking a linear increase from 0 km/h to 220 km/h is

considered. The maximum available torque at the wheel is conservatively approximated by [21]:

$$T_{available} = F_{wheel} \cdot r_w \quad (3)$$

To ensure certification safety and avoid interference with braking or ground handling performance, only a small fraction of available torque is extracted:

$$P_{rot}(t) = \eta_{rot} \cdot T_{available} \cdot \omega(t) \quad (4)$$

η_{rot}=0.0004, corresponding to 0.04% torque extraction, selected to represent a certification-safe upper bound. This value corresponds to a conservative value from the values found in literature. This formulation ensures harvested power scales linearly with taxi and landing speed.

2.4.2 Piezoelectric Energy Harvesting Model

Piezoelectric harvesting is modeled as two components [22]:

(1) Rolling-induced vibration power:

$$P_{piezo}(t) = \eta_{Piezo} \cdot P_{ref} \cdot \left(\frac{v(t)}{v_{takeoff}}\right) \quad (5)$$

P_{ref}= 800 W represents structural mechanical energy available under high-speed loading and η_{Piezo}= 0.05 represents an aggressive but realistic upper-bound electromechanical conversion efficiency [8].

(2) Touchdown impact pulse:

$$P_{impact}(t) = P_{peak} \cdot e^{-\left(\frac{t-t_{landing}}{\sigma}\right)^2} \quad (6)$$

The maximum electrical power generated during the landing impact event P_{peak}=60 W, and the temporal spread of the impulse, σ=0.07 s and effective impact durations $t - t_{landing} \approx$ 0.3 s represent short-duration high-strain vibration immediately after touchdown [11].

2.4.3 Thermoelectric Energy Harvesting Model

Brake heating during landing roll is modeled as an exponentially decaying heat source [23]:

$$P_{thermal}(t) = P_{thermal_{peak}} \cdot e^{-\frac{t-t_{landing}}{\tau}} \quad (7)$$

$$\text{for } t \geq t_{landing}$$

where $P_{thermal,Peak}$=250 W and τ =15 s corresponds to the peak electrical power level with realistic thermoelectric generator (TEG) electrical output from high-energy braking events with η_{TEG} =0.04 corresponding with practical TEG conversion efficiencies in high-temperature aerospace environments [10].

2.4.4 Total available energy

Total harvested electrical power is calculated as:

$$P_{total}(t) = P_{rot}(t) + P_{piezo}(t) + P_{impact}(t) + P_{thermal}(t) \quad (8)$$

The total recoverable electrical power is obtained by combining contributions from rotational, piezoelectric, thermoelectric, and touchdown impact harvesting mechanisms throughout the mission. The composite power signal is then integrated over time using a discrete time-stepping approach to compute the cumulative harvested energy in watt-hours, capturing transient events such as landing impact spikes and brake thermal decay.

The exact values for the harvested electrical power depend on the finally selected and implemented EH system. The efficiencies available in the implemented system (η_{rot}, η_{Piezo} and η_{TEG}) will depend on the selected hardware solution. Being the nature of this paper a feasibility study, engineering judgement combined with published values and manufacturer's data sheets were used for determining the used efficiencies.

3. Results

The developed time-domain model was implemented numerically using a Python script to evaluate the instantaneous and cumulative electrical power generation across a representative mission cycle.

Figure 2 shows the relative contributions of rotational, piezoelectric, and thermoelectric harvesting mechanisms, while highlighting the temporal dominance of specific energy sources during distinct operational phases. Particular emphasis is placed on peak power events during landing and braking, as well as the overall recoverable energy available for low-power aircraft monitoring subsystems.

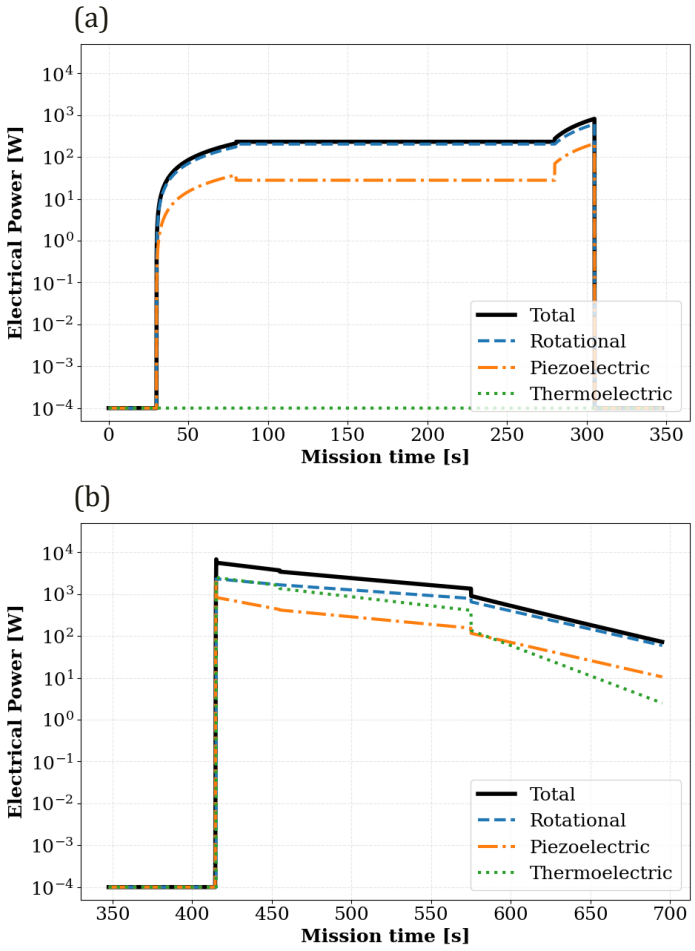

Figure 2. Simulated Time-Domain Power Contribution of Rotational, Piezoelectric, and Thermoelectric Harvesting Mechanisms (Note logarithmic scale) (a) Take off phase including taxi, rolling and take-off (b) Landing phase including landing, taxi and stop. Note Flight phase is not considered.

The numerical simulation of the multi-mode landing gear energy harvesting model reveals a strongly phase-dependent energy generation profile, with landing and taxi operations contributing the majority of recoverable electrical energy. Integration of the composite power signal over the full 695 s mission cycle yields a cumulative energy of approximately 155–160 Wh per operational sequence. Landing alone accounts for ca. 51 Wh, representing the largest single-phase contribution, resulting from the combined effects of rotational harvesting, touchdown-induced vibration, and thermoelectric conversion during brake cooling. Taxi operations, including taxi-start, taxi-cruise, and post-landing taxi, contribute approximately 100 Wh due to sustained wheel rotation and associated vibration energy, while take-off contributes approximately 4 Wh owing to its short duration despite elevated wheel rotational speeds. Instantaneous power peaks occur during landing, reaching transient levels on the order of 10^3 W, dominated by brake thermal dissipation, whereas steady-state rotational harvesting during taxi remains in the 10^2 W range. Piezoelectric harvesting contributes at the 10^0–10^1 W scale during rolling phases with a short-duration impact enhancement at touchdown. These results demonstrate that while propulsion-scale recovery is unrealistic, the harvested energy is more than sufficient to support distributed low-power subsystems, including landing gear health monitoring, brake thermal sensing, tire pressure monitoring, and edge data acquisition systems, as suggested from the table 2. The power requirements in table 2 correspond to the peak subsystem demand for the complete monitoring subsystem from a variety of data sheets of commercially available systems.

Table 2. Phase centric energy application feasibility mapping (LGHM landing gear health monitoring, BTHM brake and thermal monitoring, TPMS tire pressure monitoring, DAQ data acquisition

Use Case	Peak Subsystem power	Taxi (~100 Wh)	Takeoff (~4 Wh)	Landing (~51 Wh)
LGHM	5–10 W	Fully powered	Intermittent only	Fully powered
BTHM	5–8 W	Limited relevance	Limited relevance	Fully powered
TPMS	3–6 W	Fully powered	Burst only	Fully powered
DAQ	3–5 W	Fully powered	Short burst	Fully powered

4. Certification and Integration Considerations

Although the proposed hybrid energy harvesting system demonstrates sufficient energy generation to

power representative landing gear monitoring systems, practical implementation requires consideration of certification and integration within the aircraft environment. Since the harvested energy is intended to support maintenance-oriented sensing rather than flight-critical functions, the certification burden can be substantially reduced by classifying the proposed architecture as a non-essential monitoring system. Under this approach, loss of harvested power or sensor functionality would not affect aircraft controllability or operational safety, but would only reduce the availability of maintenance information. Consequently, fail-silent behaviour, whereby the monitoring system ceases operation without affecting aircraft functions, represents the preferred implementation strategy.

From an integration perspective, the primary engineering challenges include structural attachment of sensors to certified landing gear components, electromagnetic compatibility of wireless communication, survivability under high vibration and braking temperatures, intermittent harvested power availability, and software integrity for onboard data acquisition. These challenges can be mitigated through non-invasive mechanical attachment methods, local energy storage and power management, wireless communication compliant with aviation electromagnetic compatibility requirements, and physical isolation from flight-control systems.

Table 3. Certification and integration considerations for representative landing gear sensing applications [24], [25], [26].

Use Case	Certification Challenge	Proposed Mitigation	Certification Impact
LGHM	Structural attachment, EMI/EMC, intermittent power	Non-invasive mounting, fail-silent operation, maintenance-only reporting	Minor / No Safety Effect
BTHM	High temperature, thermal coupling, vibration	Thermal isolation, local processing, independent power supply	Low–Medium
TPMS	RF interference, wireless reliability,	Low-power certified wireless communication,	Moderate
	sensor integrity	fail-silent architecture	
DAQ	Data integrity, shock loading, software reliability	Local storage, isolated interfaces, shock-qualified hardware	Moderate

Accordingly, the proposed architecture is considered suitable for condition monitoring, structural health monitoring, tire pressure monitoring systems (TPMS), brake thermal monitoring, and maintenance event recording, while excluding safety-critical functions such as anti-skid control, weight-on-wheel logic, or braking actuation. Table 3 provides a summary of the principal certification and system integration considerations associated with each proposed sensor application, together with practical mitigation measures intended to facilitate compliance with aviation certification requirements.

5. Conclusion

The present work has presented a phase-resolved feasibility study of multi-mode energy harvesting integrated within an aircraft landing gear subsystem. The study quantitatively maps representative sensor power demands to three complementary harvesting mechanisms. It is demonstrated that meaningful electrical energy can be recovered during ground operations without compromising conservative operational constraints. The results obtained from this study indicate a strong phase dependency. It is evident that taxi operations provide the largest cumulative energy contribution through sustained rotational harvesting, take-off contributes limited but measurable energy, and landing remains the most energy-intensive harvesting phase due to the simultaneous availability of impact loading, wheel rotation, and brake heat dissipation. Beyond demonstrating energy feasibility, the study also considers the practical certification implications associated with integrating energy-harvesting-powered sensing systems into aircraft landing gear. By focusing on maintenance-oriented, non-essential sensor applications with fail-silent operation and no interface to flight-critical systems, the proposed architecture presents a realistic pathway towards

certification while minimizing integration complexity and safety impact.

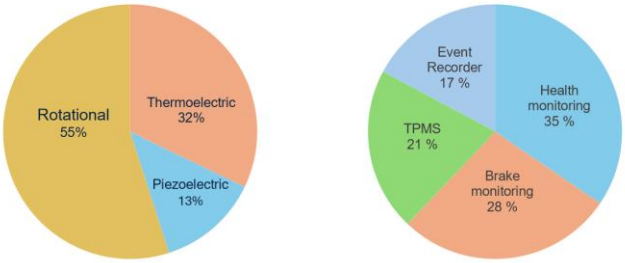

Figure 3. Relative contribution of landing gear energy harvesting mechanisms and power demand distribution of representative onboard sensor systems.

When integrated across mission phases, the harvested energy as represented by the total generated power distribution in figure 3, can be directly mapped against the total power consumption distribution of representative landing gear sensor systems. This comparison shows that the available energy is sufficient to support key functions such as structural health monitoring, tire pressure monitoring systems (TPMS), brake monitoring, and event logging. The alignment between generated and consumed power across mission phases highlights that, particularly with duty-cycled and phase-aware operation, the energy harvesting system can effectively meet onboard sensor demands. The certification assessment further indicates that these applications can be implemented with a comparatively low certification burden by ensuring non-invasive installation, electromagnetic compatibility, fail-silent behaviour, and functional isolation from aircraft flight-control systems. Future development should focus on experimental validation under representative vibration and thermal loading, refinement of efficiency models, and the integration of intelligent ultra-low-power power management electronics capable of phase-aware scheduling and adaptive duty control. It is imperative that certification-conscious implementation is prioritized, with initial applications targeting non-essential, maintenance-oriented sensor systems in order to minimize integration risk. In addition to assessing the standalone feasibility of the proposed solution, this work provides a foundation for a more extensive transition towards distributed, wire-reduced sensing architectures in more-electric aircraft. While harvested energy is not intended to replace primary aircraft power systems, it can realistically sustain localized sensor networks during ground operations.

References

[1] N. S. Currey, Aircraft Landing Gear Design: Principles and Practices. Washington, DC: AIAA Education Series, 1988.

[2] FAA, System Safety Analysis and Assessment for Part 23 Airplanes, Advisory Circular AC 23.1309-1E, 2016.

[3] SAE International, Tire Pressure Monitoring Systems (TPMS) for Aircraft, SAE ARP6137, 2016.

[4] C. R. Farrar and K. Worden, "An introduction to structural health monitoring," Philosophical Transactions of the Royal Society A, vol. 365, pp. 303–315, 2007.

[5] R. Severino, R. Gomes, M. Alves, P. Sousa, L. F. Ramos, R. Aguilar, E. Tovar, and P. B. Lourenço, "A wireless sensor network platform for structural health monitoring: Enabling accurate and synchronized measurements through COTS+custom-based design," IFAC Proceedings, vol. 43, no. 17, pp. 375–382, 2010.

[6] S. Zelenika, Z. Hadas, S. Bader, T. Becker, P. Gljušćić, et al., "Energy harvesting technologies for structural health monitoring of airplane components—A review," Sensors, vol. 22, 2020.

[7] T. G. Lim, S. P. Beeby, N. R. Harris, et al., "Energy harvesting from low-frequency vibration for tire pressure monitoring systems," IEEE Transactions on Industrial Electronics, vol. 56, no. 11, pp. 4366–4373, 2009.

[8] S. Roundy and P. K. Wright, "A piezoelectric vibration-based generator for wireless electronics," Smart Materials and Structures, vol. 13, no. 5, pp. 1131–1142, 2004.

[9] H. Fu, X. Mei, D. Yurchenko, S. Zhou, S. Theodossiades, K. Nakano, and E. M. Yeatman, "Rotational energy harvesting for self-powered sensing," Joule, vol. 5, no. 5, pp. 1074–1118, 2021.

[10] I. L. Tobi, "Feasible application of thermoelectric generators in light aviation," Energy, vol. 313, 2024.

[11] Y. Xu, W. Zhang, and Z. Fan, "System implementation trade-offs for low-speed rotational energy harvesting," Sensors, vol. 21, no. 18, 2021.

[12] X. Du, S. Zhao, and D. Wang, "Effect of friction characteristics on the vibration response of a

coupled landing gear–wheel brake structure," in Proc. SPIE Smart Structures and Materials: Fourth Int. Conf. on New Materials, Machinery, and Vehicle Engineering, vol. 13953, Mar. 2025, pp. 1–8.
[13] W. Liu, Y. Wang, and Y. Ji, "Landing impact load analysis and validation of a civil aircraft nose landing gear," Aerospace, vol. 10, no. 11, 2023.
[14] D. Gadow and M. Jiménez, "Carbon fiber-reinforced carbon composites for aircraft brakes," American Ceramic Society Bulletin, vol. 98, pp. 28–34, 2019.
[15] D. Champier, "Thermoelectric generators: A review of applications," Energies, vol. 10, no. 2, 2017.
[16] N. Ayala, S. Kearns, E. Irving, S. Cao, and E. Niechwiej-Szwedo, "Investigating the role of flight phase and task difficulty on low-time pilot performance, gaze dynamics and subjective situation awareness during simulated flight," Journal of Eye Movement Research, vol. 17, no. 1, pp. 1–28, 2024.
[17] K. Worden, C. R. Farrar, G. Manson, and G. Park, "The fundamental axioms of structural health monitoring," Proceedings of the Royal Society A, vol. 463, pp. 1639–1664, 2007.
[18] C. Bowen and M. Arafa, "Energy harvesting technologies for tire pressure monitoring systems," Advanced Energy Materials, vol. 5, 2014.
[19] E. Sazonov, K. Janoyan, and R. Jha, "Wireless intelligent sensor network for autonomous structural health monitoring," in Proc. SPIE, vol. 5384, pp. 305–314, 2004.
[20] D. Kleppner and R. Kolenkow, An Introduction to Mechanics, 2nd ed. Cambridge: Cambridge University Press, 2014.
[21] J. L. Meriam and L. G. Kraige, Engineering Mechanics: Dynamics, 8th ed. Hoboken, NJ: Wiley, 2016.
[22] C. Covaci and A. Gontean, "Piezoelectric energy harvesting solutions: A review," Sensors, vol. 20, no. 12, 2020.
[23] Q. Meng, H. Shen, B. Li, and Z. Jiao, "Full-scale simulation and experimental study of heat transfer in landing gear brake discs for medium-sized passenger aircraft," Applied Sciences, vol. 15, no. 6, 2025.
[24] RTCA, Inc., DO-160G: Environmental Conditions and Test Procedures for Airborne Equipment, Washington, DC, USA, 2010.
[25] RTCA, Inc., DO-178C: Software Considerations in Airborne Systems and Equipment Certification. Washington, DC, USA, 2011.
[26] SAE International, ARP4761: Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment. Warrendale, PA, USA, 1996.