World Journal of Advanced Engineering Technology and Sciences

eISSN: 2582-8266

Cross Ref DOI: 10.30574/wjaets

Journal homepage: https://wjaets.com/

(Research Article)

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Design and development of a remote-controlled robotic system for real-time brake temperature monitoring in aerospace application

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World Journal of Advanced Engineering Technology and Sciences, 2026, 19(02), 048-060

Publication history: Received on 31 March 2026; revised on 11 May 2026; accepted on 13 May 2026

Article DOI: https://doi.org/10.30574/wjaets.2026.19.2.0258

Abstract

A remote-controlled robotic system for real-time brake temperature monitoring makes use of contactless, high-speed infrared (IR) sensors, often mounted on specialized robotics or vehicles, to measure the surface temperature of disc. The design enables remote monitoring, enabling predictive maintenance, downtime reduction and enhanced safety by detecting excessive heat. Aircraft F-35 Brake generate substantial kinetic energy, causing brake disc temperatures to reach 600 to 1400 degrees Celsius. At these temperatures, hydraulic oil in the pipelines may carbonize, and the braking servo valve, which is highly sensitive to oil contamination, can become clogged. Therefore, design and fabrication of a remote-controlled robotic system for real-time temperature monitoring for F-35 jet brake system using 3D printing technology. The solution incorporates an advanced technology to provide live feedback through a color-coded light system: a red light which indicates that the system has exceeded a specified threshold temperature, while a green light denotes normal operating conditions.

Keywords: Brake; Aerospace; 3D Printer; Robotic system

1. Introduction

The aerospace industry has significantly enhanced connectivity by enabling swift, long-distance transportation and global trade [1]. These advancements result from the integration of operational safety practices, well established scheduled maintenance plans, and highly reliable components such as robotic braking system in modern aircraft. Together, these factors ensure aircraft safety, efficiency, and dependability across global air transport networks. The reliability and availability of the landing gear wheels and brakes (W&B), are closely related to other important aircraft subsystems [2]. These are essential for safe and frequent operations. Routine, planned maintenance is crucial for sustaining W&B performance, ensuring safe landings, effective deceleration, and safe ground maneuvering, while reducing the risk of failures during critical flight phases. However, despite regular maintenance, operational interruptions may still occur due to technical defects, resulting in unscheduled maintenance interventions that can impose substantial failure cost on airlines [3]. Therefore, minimizing unscheduled maintenance and optimizing operational schedules are key objectives.

This study seeks to design and fabricate a remote-controlled robotic system for real-time temperature monitoring of the F-35 jet brake system using 3D printing technology. The proposed solution incorporates advanced technology to provide live feedback through a color-coded light system: a red light indicates that the system has exceeded a specified threshold temperature, while a green light denotes normal operating conditions. To guide the development of this approach, a comprehensive literature review was conducted to critically assess prior research in relevant domains. This review article offers an integrated overview of the key areas that require further investigation before progressing

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toward the development of a condition-monitoring and prediction framework for aircraft landing gear wheels and brakes.

2. Literature Review

One of the critical subsystems within the landing gear assembly is the landing brake, which is activated during takeoff, landing, ground taxiing, and stationing [4]. The safety of modern aircraft relies on the reliable operation of this system [5]. Conventional brake systems utilize hydraulic pressure generated by an engine-driven pump (EDP), which transmits pressure through long, narrow pipelines [6]. This configuration presents challenges such as noise and vibration, potentially reducing pipeline lifespan and causing damage to the hydraulic system or the aircraft.

Aircraft F-35 Brake generate substantial kinetic energy, causing brake disc temperatures to reach 600 to 1400 degrees Celsius [7]. At these temperatures, hydraulic oil in the pipelines may carbonize, and the braking servo valve, which is highly sensitive to oil contamination, can become clogged [8]. Obstruction of the valve's pilot stage may compromise brake functionality and increase the risk of aircraft accidents [9].

Past studies aimed to enhance the safety and maintenance of aircraft actuation systems, including conventional brake systems. The power-by-wire (PBW) concept and the more-electric aircraft (MEA) approach have received significant attention[10]. Considering, the Electro-hydrostatic actuators (EHA) and Electro-Mechanical Actuators (EMA) in these studies. EHA was implemented in the flight control systems of the A380 and F-35, requiring over 15 years to progress from technology readiness level (TRL) 4 to TRL 9 [11]. For braking systems, EMA was adopted in the B787, where multiple motors around the wheel stators drive a screw mechanism that converts angular displacement into linear motion to generate brake torque [12]. However, limited displacement necessitates EMA motors to operate in torque-control mode, resulting in overload and excessive heat generation, which restricts continuous operation. Currently, all-electric brake systems are less mature than hydraulic systems and have not been adopted in the latest commercial aircraft, such as the A350 [13].

Researchers continue to explore improved solutions. Yao et al. [14] proposed a micro-displacement brake actuating mechanism based on piezoelectric ceramics, which demonstrated satisfactory performance except for low brake torque, limiting its application to vehicles. Karakoc et al. [15] introduced a magnetorheological brake system and evaluated various materials, confirming the feasibility of this approach. Ziabska et al. [16] developed a detailed model and presented test results for electrorheological fluid, suggesting it may offer a cleaner alternative to traditional clutches or brakes [16]. Although these materials have been applied in small devices and industrial machines, their adoption in aviation is limited by low power density and restricted brake torque. Researchers are also investigating the mechanical and thermal properties of functionally graded materials (FGMs), which exhibit gradual variation in composition and structure. FGMs may be suitable for aircraft brake systems to isolate heat loads and protect hardware. Yang et al. implemented on/off valves in servo control systems, achieving high position tracking accuracy and demonstrating a width modulation method for velocity adjustment [17]. However, their system used gas rather than hydraulic fluid and did not address force or pressure control.

Due to the displaced the hydraulic interface in aircraft brake systems and evaluation of the feasibility of on/off valves for pressure control, this study introduces a remote-controlled robotic system powered by a compact local motor. This design eliminates the need for a hydraulic supply, reducing system weight by removing components such as shutoff valves and hydraulic pipelines. Disconnecting the brake system from the airborne hydraulic network increases resistance to contamination and lowers oil cleanliness requirements, thereby improving system robustness. The all-electric interface also improves maintainability and ensures continued operation and safety, particularly when the airborne hydraulic source is unavailable.

2.1. Landing Gear Wheels and Brakes

The development of wheeled landing gear systems commenced shortly after the Wright Brothers' inaugural flight in 1903 [18]. By 1906, Santos-Dumont's "No. 14 bis" represented one of the earliest documented uses of wheeled gear in Europe. This advancement was rapidly adopted by aircraft constructed between 1907 and 1909 by pioneers such as Voisin, Farman, Bleriot, and Curtiss, each achieving significant milestones in aviation [19]. The onset of World War I, landing gear designs had largely converged on tailwheel configurations, characterized by robust support structures and basic shock absorbers [20]. Because landing gear remains attached to the aircraft throughout flight but is only utilized during taxiing, take-off, and landing, it must be engineered to be as lightweight as possible without compromising safety. Designers ensure that landing gear can withstand all certified worst-case loads and thermal conditions, including landing impact, braking during rejected take-offs, taxiing, ground handling, and cumulative wear [21]. Subsequently, the mass of structural and moving components is minimized through advanced engineering and the selection of high-strength, lightweight materials[22]. These foundational approaches established the basis for contemporary landing gear systems and facilitated ongoing enhancements in structural integrity, energy absorption, and reliability. The landing gear system is fundamental to safe ground operations, enabling controlled take-off, taxiing, and landing [23]. Its primary function is to absorb and distribute the substantial forces generated during landing and ground maneuvers, transferring these loads safely to the aircraft structure. Additionally, landing gear supports ground steering, braking after landing or during low-speed movement [24], and, for large aircraft, accommodates towing and pushback by airport vehicles. Proper wheel number and arrangement ensure optimal weight distribution [25], preventing damage to airport surfaces. Thus, the landing gear system is indispensable for safe and efficient ground operations, fulfilling both primary and secondary roles necessary for damage-free aircraft operation [26].

Wheels and brakes constitute essential components of the landing gear system, providing deceleration and directional control during ground operations [27], particularly during landings and aborted takeoffs. Contemporary aircraft predominantly employ carbon–carbon composite brakes, which offer superior performance at elevated temperatures and greater efficiency compared to conventional steel brakes [28].

Modern transport aircraft incorporate an extensive array of sensors within landing gear wheels and brake assemblies to fulfill three primary objectives: enabling critical control systems such as antiskid and autobrake, safeguarding hardware through monitoring of overheating and wear, and supporting maintenance planning to improve dispatch reliability. Although system architectures vary among manufacturers and suppliers, standard configurations include wheel-speed transducers mounted on the axle to supply data to the Brake and Steering Control Unit (BSCU) for slip regulation [29], brake-temperature probes embedded within the brake structure to detect overheating, and tire-pressure transducers that communicate pressure data via wired or wireless networks. Wireless solutions, such as Smart-Stem systems, replace traditional valve stems and transmit data to a Tire and Brake Monitoring Unit (TBMU) [30]. In electric brake systems, integrated sensors for position, load, and wear facilitate localized health monitoring. Data from these sensors is typically processed by a TBMU or BSCU, transmitted to cockpit display systems such as the Engine Indicating and Crew Alerting System (EICAS) or the Electronic Centralized Aircraft Monitor (ECAM), and archived for maintenance diagnostics and record-keeping.

2.2. Wheel-Speed Sensors

Wheel-speed sensing is widely used on aircraft wheels to support antiskid (anti-lock) brake control[31]. These sensors monitor changes in wheel rotation and transmit corresponding analog or digital signals to the brake control system and related monitoring components[32]. There are two main types of wheel-speed sensors: alternating-current (AC) and direct-current (DC) systems. Both operate similarly, differing only in sensor design and control unit electronics.

In AC-based systems, the wheel-speed sensor functions as a variable AC generator [33]. It consists of a permanent magnet surrounded by a pickup coil, positioned inside the landing gear axle. The sensor features four evenly spaced poles with external teeth. A soft-iron exciter ring, with teeth on its inner surface, is mounted inside the wheel hubcap and rotates around the sensor. As the wheel turns, the movement between the sensor poles and exciter ring teeth causes periodic changes in the magnetic circuit, generating an alternating current in the pickup coil [34]. The frequency of this current corresponds to the wheel's speed. The control unit then converts this AC signal into a DC voltage for the brake control system.

2.3. Brake Temperature Probes

Brake Temperature Monitoring Systems typically use Resistance Temperature Detectors (RTDs) to estimate brake stack temperature [35]. RTDs measure changes in electrical resistance, usually in platinum, as temperature varies. These systems in commercial aircraft operate across a wide range, from −100 °C to +815 °C[36]. Brake temperature plays a key role in carbon-brake wear. In most large passenger aircraft, the brake-temperature probe is installed near the center of the heat pack, as shown in Figure 1. This placement provides a representative measurement for hot-brake advisories, landing-gear retraction, and dispatch decisions to prevent tire or wheel overheating. Because the probe tip is not in direct contact with the carbon disks and a small gap exists, the indicated temperature lags behind the actual disk temperature due to heat-soak effects and radiative heat transfer. As a result, landing gear health-monitoring functions that depend on brake temperature, such as hot-brake detection, cooling-time estimation, and brake drag detection, require measurement hardware and algorithms that compensate for this delay to ensure timely and accurate data.

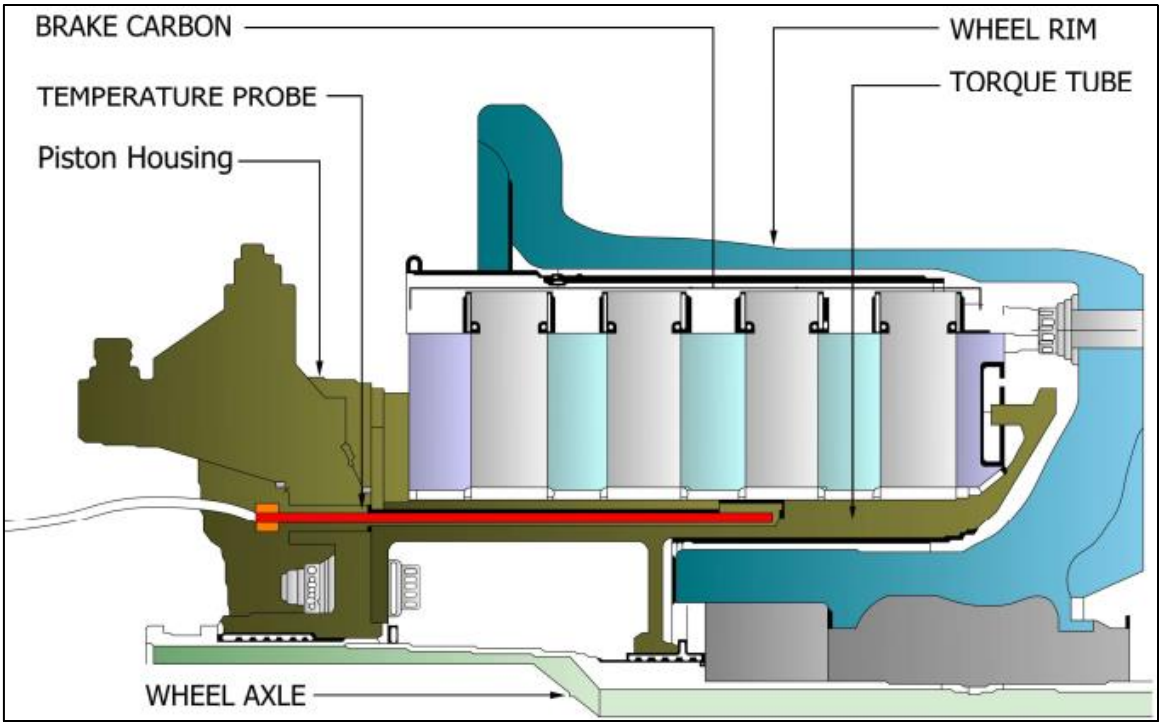

Figure 1 Brake temperature probe location [37]

The brake carbon is the main component responsible for generating friction and heat within the brake stack. A temperature probe, positioned next to the carbon discs through the piston housing in the torque tube, measures the brake's temperature as shown in Figure 1. The piston housing and torque tube secure the probe. The wheel axle connects the wheel and brake assembly to the landing gear and supports loads during ground operations. The wheel rim, shown in blue, encloses the brake assembly and supports the tire.

2.4. Tire Pressure Transducers

An aircraft tire pressure monitoring system (TPMS) electronically measures and reports tire inflation pressure [38]. Implementations range from systems that transmit data to the flight deck to those intended solely for ground-based maintenance. The literature identifies three primary system architectures:

- Valve-stem gauge or inflation valve assemblies equipped with a direct-reading gauge, instead of the standard inflation valve, enable maintenance crews to verify tire pressure during preflight inspections.
- Handheld reader systems employ a passive wireless sensor embedded within the valve stem, which is interrogated by a portable reader during maintenance checks.
- Cockpit-displayed systems use a pressure sensor mounted on the wheel to directly measure tire pressure, while an electronics module at the wheel hub supplies transducer excitation and signal conditioning.

The measured output is digitized and transmitted across the axle using a rotating transformer to a processor, such as a tire pressure indicating unit [39]. This processor decodes the data, compares actual pressures with preset thresholds (including both absolute and cross-axle differential values), and initiates cockpit alerts as necessary. Tire pressures may also be displayed to the flight crew on demand; see Figure 2 for a representative TPMS architecture. Building on these concepts, TPMS is now widely available as an integrated option. A prominent example is Crane's Smart Stem, a passive wireless pressure and temperature sensor that replaces the inflation valve stem and communicates via an in-axle transceiver to a tire and brake monitoring unit (TBMU). Reported benefits include increased tire life, reduced line-maintenance requirements, and elimination of wiring on rotating hardware, positioning these systems as a viable alternative to fully wired implementations.

Figure 2 Aircraft Tyre Pressure Monitoring System

3. Design Concept

3.1. Mounting Frame

The 80/20 aluminum frame structure depicted in the figure serves as the foundational platform for the development of a remote-controlled robotic system designed for real-time brake temperature monitoring in the aerospace industry. This modular frame design yields a lightweight, reconfigurable, and mechanically robust architecture that is well suited for the integration of sensing, actuation, and control subsystems required for high-performance applications.

The rectangular prism configuration of the 80/20 frame, as illustrated in Figure 2, offers a rigid yet adaptable enclosure for mounting essential components such as infrared temperature sensors, thermal cameras, embedded controllers, communication modules, and power systems. Aluminum was selected for the extrusion profiles because of its high strength-to-weight ratio, corrosion resistance, and ease of assembly using standardized T-slot connections. This modular approach facilitates rapid prototyping, iterative design modifications, and scalability to accommodate mission-specific requirements.

Figure 3 80/20 Framing

3.2. 3D Printed Arm and Temperature Sensor

A 3D-printed robotic arm incorporating a temperature-sensing unit was developed for real-time brake temperature monitoring in small units for aerospace applications. This component is designed to provide precise sensor positioning and thermal reading accuracy in ambient operational environments, such as aircraft landing gear assemblies.

The Robotic arm was fabricated with the aid of a 3D Printer (Airwolf 3D – Costa Mesa, California, USA), enabling rapid prototyping and manufacturing of complex geometries that are difficult to achieve in traditional manufacturing. Low-density polymer materials were used, which reduces overall system mass while maintaining sufficient structural integrity for vibrational purposes. The elongated arm geometry allows the sensing unit to be extended toward brake surfaces while maintaining a safe distance between the primary robotic platform and high-temperature zones.

At the base of the robotic arm, a compact servo motor was mounted on a circular platform, providing rotational motion and enabling controlled angular positioning of the arm. This actuation mechanism enables the system to dynamically adjust the sensor orientation, ensuring optimal line-of-sight for temperature measurement across different brake configurations. The servo-driven design supports remote operation, making it suitable for hazardous or inaccessible aerospace environments.

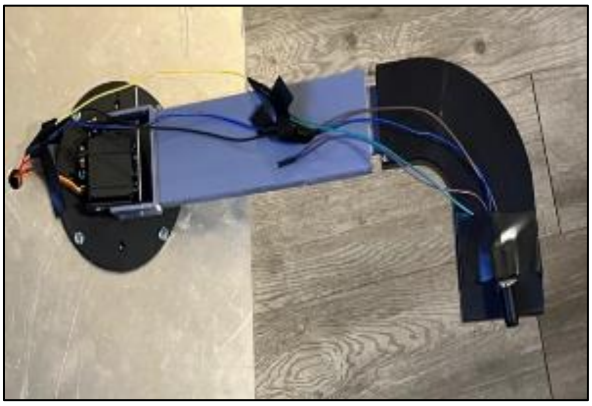

Figure 4 3D Printed Arm and Temperature Sensor

3.3. Prototype

A conceptual design for a mobile robotic platform integrated with a multi-degree-of-freedom robotic manipulator has been developed to facilitate real-time brake temperature monitoring in aerospace systems. This platform functions as the central operational unit by combining mobility, sensing, and actuation to enable remote inspection of high-temperature brake assemblies in challenging and confined environments.

The system base comprises a four-wheel-drive mobile chassis engineered for stability, maneuverability, and load-bearing capacity. Its wide wheelbase and robust wheel configuration facilitate smooth navigation across uneven or industrial surfaces commonly encountered in maintenance hangars or testing facilities. The chassis accommodates critical subsystems, including the power supply (battery pack), motor drivers, embedded control units, and communication modules, all arranged to maintain a low center of gravity and enhance operational stability.

A robotic manipulator arm with multiple degrees of freedom is mounted on the platform, enabling precise positioning of the temperature-sensing unit. The articulated design allows flexible movement in both vertical and horizontal directions, providing access to complex geometries surrounding aircraft brake systems. The manipulator is designed for seamless integration with the previously described 3D-printed sensing arm and temperature sensor module, forming a hierarchical actuation system. The primary robotic arm provides coarse positioning, while the sensor arm enables fine adjustments and targeted measurements. This dual-level control improves measurement precision and adaptability.

The system is designed to operate via remote wireless communication, enabling operators to maneuver the robot and adjust sensor positioning from a safe distance. Real-time data acquisition and transmission support continuous monitoring of brake temperature, which is essential for assessing thermal performance, detecting hotspots, and preventing failure in aerospace braking systems. The design incorporates scalability and modularity. The robotic arm, sensor module, and chassis can be independently upgraded or reconfigured to meet specific application requirements.

The platform can also be extended to include additional diagnostic sensors, such as vibration or infrared imaging systems, thereby enhancing its capability for comprehensive condition monitoring.

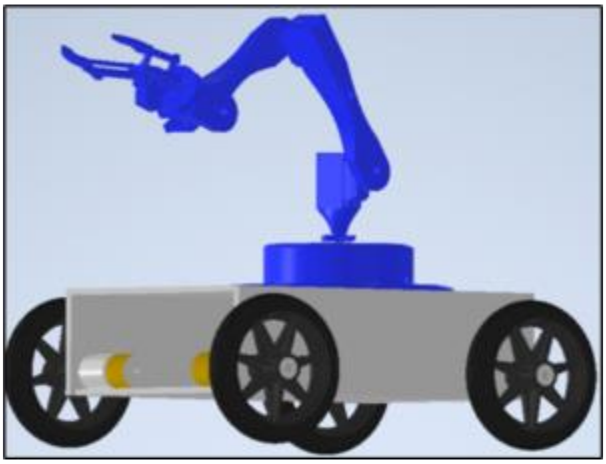	
(A) CAD Prototype Brake Temperature Robot	**(b) Final Design Brake Temperature Robot**

Figure 5 Brake Temperature Robot

4. Heat Transfer Dynamics in Aircraft Wheels and Brakes

During landing, and especially during a rejected take-off, the landing gear wheels and multi-disc carbon brakes convert a substantial portion of the aircraft's kinetic energy into heat within the brake stack [30]. This process causes rapid and highly non-uniform temperature increases at the friction interfaces, which then propagate through the discs, pressure plates, torque path, and wheel components, resulting in a transient thermal field that persists beyond the braking event. These temperature transients directly influence design margins, determining the necessary brake size and the level of thermal protection required for the wheel, tire, and fuse plugs, as well as the operational limitations imposed on airlines. Regulatory and certification guidelines define the Maximum Brake Energy (MBE) that the system can safely absorb and specify the maximum quick-turn weight (MQTW) allowed before the next departure [40]. Modeling and operational studies demonstrate how these limits translate into required cool-down times, illustrating the relationship between post-braking thermal decay and dispatch readiness. The primary challenge is to reconcile these design and turnaround constraints with the inherently space- and time-varying thermal field. Methods that rely on averaged temperatures or single-sensor readings may fail to detect local temperature peaks in the brake stack or rim, thereby compromising the protective margins assumed by MBE and MQTW criteria.

The temperature increase within the wheels and brakes assembly is governed by three interrelated factors: (i) frictional heat generation at the disc–pad interface, including flash temperatures, contact non-uniformity, and transient conduction within the friction ring; (ii) a time-dependent heat-partition ratio between rotor and stator, which is influenced by contact pressure, sliding speed, surface condition, and the thermal properties of carbon/C–SiC (carbon-fiber-reinforced silicon carbide composites), often estimated from effusivity ratios and refined through inverse identification; and (iii) post-event cooling via conduction through the torque path into the wheel and tire, forced convection to the airstream and through internal ventilation passages during roll-out or taxi, and thermal radiation within the enclosed wheel-well environment when retracted. Each mechanism varies significantly with operating conditions such as vehicle speed, brake pressure, surface state, and material properties. Furthermore, published values rarely include quantified uncertainty, making reliance on empirical estimates unreliable for analysis and decision-making. A robust likelihood ratio (LR)-informed workflow involves (a) imposing aircraft-specific boundary conditions for each operational phase, (b) identifying uncertain parameters (such as partition factor and time-varying local convective heat-transfer coefficient) using inverse methods with bench or flight data (including brake temperature monitoring systems and infrared thermography), and (c) validating on-aircraft while propagating uncertainty into MBE and MQTW cool-down predictions and maintenance decisions for wheels and brakes.

4.1. Conduction Process

The primary wheel and brake (W&B) heat transfer pathways and associated modeling methods. Following a braking event, frictional heat accumulated in the carbon stack is conducted through the pressure plate, torque tube, wheel hub, and rim, collectively referred to as the torque path as shown gin Figure 6. Due to the anisotropic nature of carbon–

carbon (C/C) heat packs, which exhibit higher in-plane than through-thickness conductivity, hot spots at the friction ring can migrate axially and subsequently radially into metallic hardware over several minutes, even as convective cooling from the runway diminishes. Coupled brake–wheel models and sensor-hardware analyses demonstrate this soak-back phenomenon: the brake cools while the wheel rim and tire continue to warm, resulting in wheel and tire temperature peaks that may occur significantly after the peak temperatures within internal brake components. This process is operationally significant because 14 CFR 25.735 (airworthiness standards for brakes and braking systems on transport-category airplanes) mandates an "over-temperature burst prevention" mechanism, typically implemented as fusible plugs. Furthermore, FAA and EASA guidance requires high-energy demonstrations to verify that the wheel, tire, and adjacent structures remain protected throughout the aircraft's operational envelope. Without mitigation, radiative heat transfer would elevate rim temperatures; therefore, heat shields (chin rings) are installed to increase thermal resistance and reduce direct exposure to hot surfaces, which has been shown to lower rim and tire heating during service.

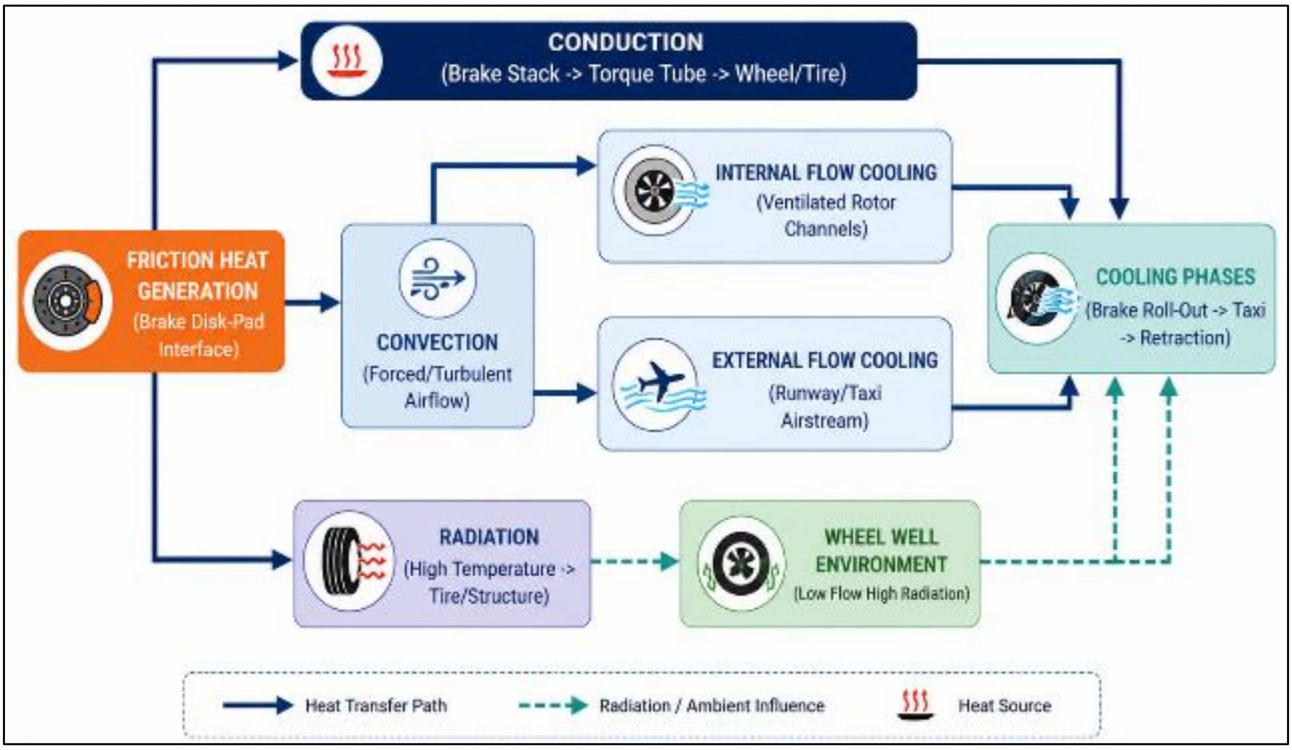

Figure 6 Aircraft wheel and brake heat transfer pathways

Comprehensive conduction analyses should include anisotropic carbon properties, contact conductance at interfaces such as the backplate and torque-tube splines, as well as the thermal mass and boundary conditions of the wheel and tire, including factors like inflation gas and rim thickness. Validated finite element studies of aircraft wheel–brake assemblies indicate that omitting these couplings may result in underestimation of rim temperatures and fuse-plug margins.

4.2. Convection Process and Wheel Brake effect

During the landing roll-out and taxi phases, convection serves as the primary mechanism for heat removal from the wheel brake assembly. External convection results from forced cross-flow generated by the runway and taxi airstream, which moves over the wheel rim and exposed brake surfaces. Simultaneously, internal convection is induced by the pumping action of the rotating brake rotor, which generates through-flow within ventilated passages and inter-disc gaps. This circulation introduces cooler air into the brake cavity and expels heated air radially outward, establishing the internal flow pathways.

The behavior of these flow fields is extensively documented in the literature on rotating-disk and rotor stator cavities[41]. This research demonstrates how Reynolds number, flow regime, and geometric configuration affect local convective heat-transfer coefficients and Nusselt-number distributions. These correlations are frequently utilized in aircraft brake thermal models. Notably, studies indicate that convective heat transfer typically increases with radial position due to higher tangential speeds, and that cavity through-flow improves cooling effectiveness at the outer annulus.

Computational Fluid Dynamics (CFD) studies further reveal that parameters such as vane count, vane angle, and inter-disc gap ratio significantly influence internal flow development [42]. Narrow, well-defined gaps promote increased shear and turbulence, thereby enhancing heat transfer, while excessively large gaps diminish the rotor-pumping effect and reduce local cooling. CFD analyses also show that specific cavity geometries can create recirculation zones near the hub or behind misaligned vanes, resulting in lower local Nusselt numbers and thermal non-uniformity across the brake rotor. Spatial and temporal variations in the convective heat-transfer coefficient, h(r,θ,t), significantly affect the transient thermal response of the brake stack during roll-out and taxi. As a result, phase-dependent convection models, based on reduced-order correlations or CFD solutions, are employed to define boundary conditions for finite-element simulations. This methodology enables evaluation of brake cooling performance, quick-turn readiness, and adherence to maximum brake energy and minimum-cooling-time requirements. The integration of classical rotating-disk theory with aircraft-specific CFD studies ensures that internal and external convection remain central to predicting post-landing brake temperatures.

Since convective capacity decreases rapidly with speed, being proportional to the square of velocity, cooling during the taxi phase is substantially less effective than during one-runway operations, thereby increasing the importance of conduction and soak-back. Conceptual studies indicate that ducted wheel-well ventilation or moderate forced flow can substantially enhance brake cooling during ground operations with minimal drag penalties. For accurate aircraft-specific predictions, boundary conditions should be adjusted according to operational phase, transitioning from high-Reynolds-number cross-flow during roll-out to *low-Reynolds-number* external convection during taxi, while also considering internally pumped flows in ventilated rotors. Reliance on generalized correlations without phase-specific updates often leads to inaccurate estimates of cooling times and quick-turn limits.

4.3. Radiation and Wheel Brake Effect

Following gear retraction, the bulk airflow within the wheel-well bay becomes weak. Consequently, the brake–wheel assembly shifts from a convection-dominated regime to one governed by enclosure radiation, with conduction playing a comparatively minor role [43]. In this scenario, net heat exchange is determined primarily by geometric view factors among the hottest brake surfaces (such as friction rings and back-plates), the wheel rim and sidewall, any heat shields or liners, and the bay structure. As convective heat transfer coefficients decrease with speed, radiative heat flux, which scales with the Stefan–Boltzmann constant, the surface's total hemispherical emissivity [44], the absolute temperature of the emitting surface, and the absolute temperature of the surroundings, can dominate the early post-retraction cool-down, particularly for high-emissivity carbon surfaces. This situation warrants the application of gray/diffuse enclosure analysis, specifically radiosity–irradiation methods with accurate view factors. Transport-airplane guidance highlights a similar hazard: for retractable-gear installations, fusible plugs alone do not provide complete protection [45], and temperature indication should be installed where overheating could damage wheel-well equipment. Therefore, the bay must be analyzed as a low-flow enclosure and monitored accordingly. Mitigation strategies address the enclosure physics. Heat shields or liners (such as chin rings) with low effective emissivity facing the brake reduce the radiative view to the rim and tire, thereby decreasing net heat exchange toward the wheel [46]. This method is supported by dedicated shield designs and established service practices. Where feasible, wheel-well ventilation, achieved through small intake or extraction paths or ducted flow, is implemented to restore a modest forced-convection sink after retraction and to accelerate the cool-down of the enclosed assembly.

Post-retraction thermal models must, at a minimum, incorporate a gray/diffuse enclosure radiation approach using measured or effective emissivity values for carbon friction elements and metallic or shielded wheel surfaces. Additionally, a view-factor network that accounts for multiple reflections between closely spaced rings and shields is essential. Omitting the enclosure radiation term can result in underestimation of rim and tire temperatures and insufficient assessment of wheel-well equipment exposure, which contradicts the over-temperature protection and indication requirements specified in landing gear and retraction guidance. For operational phases preceding retraction, aircraft brake models should revert to cross-flow and cavity convection boundary conditions.

4.4. Operational Phases and Cooling Timelines

Previous research demonstrates that the relative significance of heat transfer mechanisms in aircraft wheels and brakes varies across different operational phases. During the landing roll, high external flow velocities enhance forced convection over exposed brake surfaces and through ventilated channel [47]. Studies from the rotating-disc cavity literature confirm Reynolds-number scaling of convective coefficients, and recent full-scale simulations of brake discs for medium-sized passenger aircraft further validate the predominant influence of cross-flow convection immediately following braking.

As the aircraft decelerates during taxi, cooling effectiveness decreases. Convective coefficients decline with airspeed according to the relationship Un, where U represents airspeed and n ranges from approximately 0.5 to 0.8 depending on geometry, consistent with standard Nusselt correlations. Empirical studies indicate that as convection diminishes, conductive heat transfer into the wheel rim becomes increasingly significant, often resulting in delayed temperature peaks in the rim and tire after the brake stack has begun to cool. Airbus service documentation and flight-test data confirm that brake-temperature readings, typically obtained from torque-tube or stator probes, may lag behind or under-represent the critical thermal exposure of the rim and tire [48].

After gear retraction, the cooling environment changes substantially. The wheel well becomes a low-flow enclosure where radiative heat exchange predominates until surface temperatures decrease below several hundred degrees Celsius [49]. Background studies on radiation underscore the importance of accurate emissivity data and enclosure view-factor analysis. Regulatory sources emphasize that fusible plugs alone are inadequate safeguards and that dedicated temperature monitoring and protection systems are required in the wheel well to maintain structural safety. Field trials and experimental investigations demonstrate that ducted wheel-well ventilation can restore moderate forced-flow cooling and reduce cooldown durations.

4.5. Aircraft Wheel and Brake Temperature Prediction

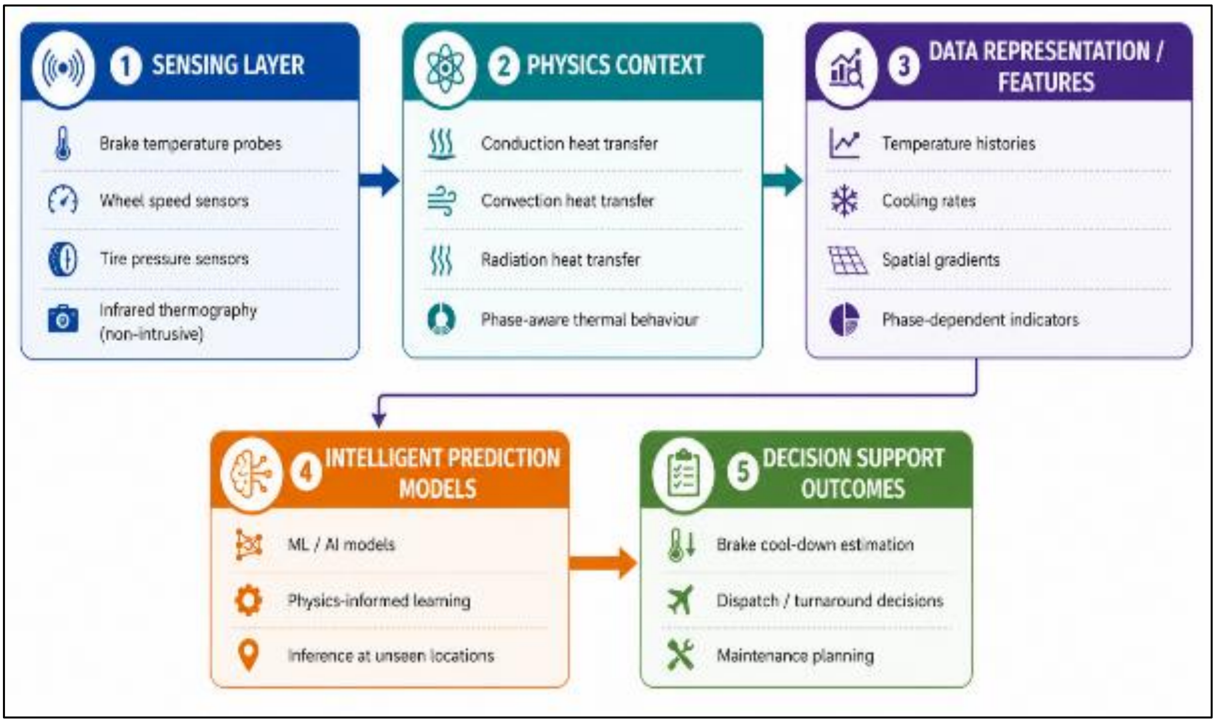

Figure 7 Conceptual integration of sensing, heat-transfer physics, and intelligent prediction models for aircraft wheel and brake temperature monitoring [52]

Historically, the development of wheel and brake temperature monitoring has progressed through several distinct stages. Early approaches relied primarily on embedded point sensors and conservative empirical limits to support operational decision-making [50], providing limited insight into spatial thermal behavior. Subsequent advances introduced physics-based thermal modeling, enabling a more comprehensive understanding of heat transfer mechanisms within the brake and wheel assembly. However, this is often at the cost of high modeling complexity and limited operational applicability. More recent research has explored data-driven, AI/ML-based prediction methods, motivated by the availability of onboard sensor data and increased computational capacity. However, these approaches have largely been constrained by sparse sensing and a lack of spatially resolved, real-flight thermal datasets [51]. As a result, current state-of-the-art efforts increasingly focus on hybrid strategies that integrate operational sensing, heat-transfer physics, and intelligent prediction models, aiming to balance physical fidelity with practical deployability. This evolution shows a shift from isolated sensing or modeling solutions to integrated frameworks that support condition monitoring and predictive decision-making under real operational constraints.

To clarify the functional interdependencies between sensing, thermal modeling, and prediction, Figure 7 presents a conceptual integration framework synthesized from the reviewed literature. Rather than proposing a specific implementation, the diagram illustrates the typical flow of information between sensing modalities, physics-based understanding of heat-transfer processes, and intelligent prediction models, highlighting how these elements collectively influence the accuracy and reliability of wheel and brake temperature prediction.

5. Conclusion

Embedded sensors in commercial aircraft are primarily point-based and do not characterize the distributed thermal state of the brake assembly. In contrast, infrared thermography offers spatially resolved temperature fields without necessitating aircraft modification. Despite its suitability for operational data acquisition, thermography has been infrequently applied in published brake-cooling studies. Utilizing this sensing modality could enable richer datasets, improved physics-based calibration, and more robust data-driven modeling. Although Machine Learning (ML) methods are widely used for engines, auxiliary power units (APUs), avionics, and structural monitoring, similar efforts for brake temperature prediction are scarce. No studies have demonstrated the use of sequence-based learning, hybrid physics-aware models, or related methods trained on operational thermal measurements. This gap presents a clear opportunity to apply modern data-driven approaches, especially when supported by enhanced sensing and systematically generated thermal datasets.

In summary, this paper identifies a promising direction that implement non-intrusive thermal measurement, and modern data-driven methods to establish a cohesive predictive framework for wheel and brake temperatures. Nevertheless, several challenges must be addressed before such a framework can be implemented in practice.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] A. R. Goetz, "Air transport: speed, global connectivity and time–space convergence," in Handbook on Geographies of Technology, Edward Elgar Publishing, 2017. doi: 10.4337/9781785361166.00023.

[2] L. S. Ramachandra, I. K. Jennions, and N. P. Avdelidis, "An In-Depth Review on Sensing, Heat-Transfer Dynamics, and Predictive Modeling for Aircraft Wheel and Brake Systems," Sensors, vol. 26, no. 3, p. 921, Jan. 2026, doi: 10.3390/s26030921.

[3] Rajee Olaganathan, "Human factors in aviation maintenance: understanding errors, management, and technological trends," Global Journal of Engineering and Technology Advances, vol. 18, no. 2, pp. 092–101, Feb. 2024, doi: 10.30574/gjeta.2024.18.2.0021.

[4] N. C. Heerens, "Landing gear design in an automated design environment." [Online]. Available: http://repository.tudelft.nl/.

[5] N. G. Leveson, "A New Approach to System Safety Engineering," 2002.

[6] Y. SHANG, X. LIU, Z. JIAO, and S. WU, "A novel integrated self-powered brake system for more electric aircraft," Chinese Journal of Aeronautics, vol. 31, no. 5, pp. 976–989, May 2018, doi: 10.1016/j.cja.2017.11.015.

[7] J. Zhou, "The Energy-Absorbing Behaviour of Novel Aerospace Composite Structures," 2015.

[8] K. Sotoodeh, "Failure Modes and Preventive Strategies in Control Valves Operating Under Harsh Conditions: A Comprehensive Analysis," Journal of Failure Analysis and Prevention, vol. 25, no. 4, pp. 1483–1493, Aug. 2025, doi: 10.1007/s11668-025-02263-y.

[9] P. Korba, R. Huňady, M. Hovanec, B. Rácek, and P. Pavelka, "Fatigue life analysis of an aircraft brake component to prevent damage and ensure operational safety," Eng. Fail. Anal., vol. 129, p. 105653, Nov. 2021, doi: 10.1016/j.engfailanal.2021.105653.

[10] J.-C. Maré, “Review and Analysis of the Reasons Delaying the Entry into Service of Power-by-Wire Actuators for High-Power Safety-Critical Applications,” Actuators, vol. 10, no. 9, p. 233, Sep. 2021, doi: 10.3390/act10090233.

[11] Stevens, JMGF, and Vreeken, “NLR-Netherlands Aerospace Centre The potential of technologies to mitigate helicopter accident factors Status update and way forward,” 2018. [Online]. Available: www.nlr.nl

[12] C. Li et al., “A Review of Electro-Mechanical Brake (EMB) System: Structure, Control and Application,” Sustainability, vol. 15, no. 5, p. 4514, Mar. 2023, doi: 10.3390/su15054514.

[13] M. E. Aguida, Y. Che, and J. Yang, “Technological advancements and future prospects of electrical power systems for sustainable more electric aircraft,” Propulsion and Power Research, vol. 13, no. 4, pp. 475–486, Dec. 2024, doi: 10.1016/j.jppr.2024.11.003.

[14] J. Yao, C. Chen, and H. Chen, “Experimental study on friction braking deceleration system based on micro displacement mechanism,” in 2017 Symposium on Piezoelectricity, Acoustic Waves, and Device Applications (SPAWDA), IEEE, Oct. 2017, pp. 260–264. doi: 10.1109/SPAWDA.2017.8340335.

[15] K. Karakoc, E. J. Park, and A. Suleman, “Design considerations for an automotive magnetorheological brake,” Mechatronics, vol. 18, no. 8, pp. 434–447, Oct. 2008, doi: 10.1016/j.mechatronics.2008.02.003.

[16] E. Ziąbska, K. Osowski, A. Kęsy, and Z. Kęsy, “ARTUR OLSZAK”, doi: 10.4467/2353737XCT.16.288.6120.

[17] X. Yang, D. Wu, C. Wang, C. Gao, H. Gao, and Y. Liu, “Adaptive fuzzy PID control of high-speed on-off valve for position control system used in water hydraulic manipulators,” Fusion Engineering and Design, vol. 203, p. 114437, Jun. 2024, doi: 10.1016/j.fusengdes.2024.114437.

[18] J. S. ALLEN, “Some Aspects of Technological Change—1900 to 1939: A Symposium,” Transactions of the Newcomen Society, vol. 55, no. 1, pp. 31–66, Jan. 1983, doi: 10.1179/tns.1983.002.

[19] B. S. de Mattos, “Open-source philosophy and the dawn of aviation,” Journal of Aerospace Technology and Management, vol. 4, no. 3, pp. 355–380, 2012, doi: 10.5028/jatm.2012.04030812.

[20] N. K. Liseitsev, “Landing Gear Design,” 2025, pp. 737–768. doi: 10.1007/978-981-96-4599-2_21.

[21] P. Maggiore and C. A. Floriani, “POLITECNICO DI TORINO FATIGUE AND HUMAN FACTOR IN AVIATION Academic Supervisor Company Supervisor Candidate Cristiano Forcella Graduation year 2020\2021.”

[22] H. Guo, X. Zhou, and Z. Liu, “Advanced Lightweight Structural Materials for Automobiles: Properties, Manipulation, and Perspective,” Sci. Adv. Mater., vol. 16, no. 5, pp. 563–580, May 2024, doi: 10.1166/sam.2024.4686.

[23] C. Frank, J.-G. Durand, W. Levy, F. Allair, and D. N. Mavris, “Design of an Improved Green Taxiing System Focused around the Landing Gear,” in 14th AIAA Aviation Technology, Integration, and Operations Conference, Reston, Virginia: American Institute of Aeronautics and Astronautics, Jun. 2014. doi: 10.2514/6.2014-3010.

[24] P. Suresh, N. K. Sura, and K. Shankar, “Investigation of nonlinear landing gear behavior and dynamic responses on high performance aircraft,” Proc. Inst. Mech. Eng. G J. Aerosp. Eng., vol. 233, no. 15, pp. 5674–5688, Dec. 2019, doi: 10.1177/0954410019854628.

[25] S. Das and C. Analyst, “Design and Weight Optimization of Aluminium Alloy Wheel,” International Journal of Scientific and Research Publications, vol. 4, no. 6, 2014, [Online]. Available: www.ijsrp.org

[26] K. Deng, A. P. Ompusunggu, Y. Xu, M. Skote, and Y. Zhao, “A Review of Material-Related Mechanical Failures and Load Monitoring-Based Structural Health Monitoring (SHM) Technologies in Aircraft Landing Gear,” Aerospace, vol. 12, no. 3, p. 266, Mar. 2025, doi: 10.3390/aerospace12030266.

[27] E. Tunca, H. Kafali, G. Keskin, and M. C. Kuşhan, “Landing Gear Systems in Aircraft,” 2022, pp. 153–179. doi: 10.1007/978-3-030-91873-6_7.

[28] R. Gadow and M. Jiménez, “Carbon fiber-reinforced carbon composites for aircraft brakes.” [Online]. Available: www.ceramics.org

[29] R. Isermann, “Designs and Specification of Mechatronic Systems,” 2023, pp. 287–313. doi: 10.1007/978-3-030-96729-1_13.

[30] L. S. Ramachandra, I. K. Jennions, and N. P. Avdelidis, “An In-Depth Review on Sensing, Heat-Transfer Dynamics, and Predictive Modeling for Aircraft Wheel and Brake Systems,” Sensors, vol. 26, no. 3, p. 921, Jan. 2026, doi: 10.3390/s26030921.

[31] F. Pretagostini, L. Ferranti, G. Berardo, V. Ivanov, and B. Shyrokau, “Survey on Wheel Slip Control Design Strategies, Evaluation and Application to Antilock Braking Systems,” IEEE Access, vol. 8, pp. 10951–10970, 2020, doi: 10.1109/ACCESS.2020.2965644.

[32] C. Pan, L. Chen, L. Chen, H. Jiang, Z. Li, and S. Wang, "Research on motor rotational speed measurement in regenerative braking system of electric vehicle," Mech. Syst. Signal Process., vol. 66–67, pp. 829–839, Jan. 2016, doi: 10.1016/j.ymssp.2015.06.001.

[33] Y. Yang et al., "Sampling-efficient path planning and improved actor-critic-based obstacle avoidance for autonomous robots," Science China Information Sciences, vol. 67, no. 5, p. 152204, May 2024, doi: 10.1007/s11432-022-3904-9.

[34] P. Kennedy, "Understanding Sensors Part 1 Sensor Technology." [Online]. Available: www.SunCam.com

[35] "Using Wheel Temperature Detector Technology to Monitor Railcar Brake System Effectiveness." [Online]. Available: http://www.fra.dot.gov.

[36] Y.-G. Lv, G.-P. Zhang, Q.-W. Wang, and W.-X. Chu, "Thermal Management Technologies Used for High Heat Flux Automobiles and Aircraft: A Review," Energies (Basel)., vol. 15, no. 21, p. 8316, Nov. 2022, doi: 10.3390/en15218316.

[37] L. Wawrzonek and R. A. Białecki, "Temperature in a disk brake, simulation and experimental verification," Int. J. Numer. Methods Heat Fluid Flow, vol. 18, no. 3/4, pp. 387–400, May 2008, doi: 10.1108/09615530810853646.

[38] S. Velupillai and L. Guvenc, "Tire Pressure Monitoring [Applications of Control]," IEEE Control Syst., vol. 27, no. 6, pp. 22–25, Dec. 2007, doi: 10.1109/MCS.2007.909477.

[39] by Chethan, V. K. Professor, and S. Prakash Kumar, "Transducers for Measurement of Draft and Torque of Tractor-implement System-A Review," 2018.

[40] N. E. Daidzic, "Modeling and Computation of the Maximum Braking Energy Speed for Transport Category Airplanes," Journal of Aviation Technology and Engineering, vol. 6, no. 2, Mar. 2017, doi: 10.7771/2159-6670.1154.

[41] M. Darvish Damavandi and A. Nejat, "Numerical investigation of fluid flow in a rotor–stator cavity with curved rotor disk," Journal of the Brazilian Society of Mechanical Sciences and Engineering, vol. 40, no. 4, p. 180, Apr. 2018, doi: 10.1007/s40430-018-1111-y.

[42] J. W. Chew and N. J. Hills, "Computational fluid dynamics for turbomachinery internal air systems," Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, vol. 365, no. 1859, pp. 2587–2611, Oct. 2007, doi: 10.1098/rsta.2007.2022.

[43] N. Czapla et al., "GROUP A-THERMAL SCIENCES Performance Testing of Unitary Split-System Air Conditioner with Viper Energy Recovery Expansion Device DEMO: High Efficiency Military ECUs (Ammar Bahman/Psychrometric chamber on west side of TS area) Station 2."

[44] O. Acikgoz, "A novel evaluation regarding the influence of surface emissivity on radiative and total heat transfer coefficients in radiant heating systems by means of theoretical and numerical methods," Energy Build., vol. 102, pp. 105–116, Sep. 2015, doi: 10.1016/j.enbuild.2015.05.016.

[45] A. M. Tsimtsios and V. C. Nikolaidis, "Towards Plug-and-Play Protection for Meshed Distribution Systems With DG," IEEE Trans. Smart Grid, vol. 11, no. 3, pp. 1980–1995, May 2020, doi: 10.1109/TSG.2019.2945694.

[46] P. Kovalenko, "HEAT TRANSFER ON WHEEL-BRAKE SYSTEM AT CRITICAL THERMAL CONDITIONS," 2021.

[47] R. A. García-León, N. Afanador-García, and J. A. Gómez-Camperos, "Numerical Study of Heat Transfer and Speed Air Flow on Performance of an Auto-Ventilated Disc Brake," Fluids, vol. 6, no. 4, p. 160, Apr. 2021, doi: 10.3390/fluids6040160.

[48] 作者, "标题."

[49] A. G. Dixon, "Fixed bed catalytic reactor modelling—the radial heat transfer problem," Can. J. Chem. Eng., vol. 90, no. 3, pp. 507–527, Jun. 2012, doi: 10.1002/cjce.21630.

[50] B. Suslu, F. Ali, and I. K. Jennions, "Understanding the Role of Sensor Optimisation in Complex Systems," Sensors, vol. 23, no. 18, p. 7819, Sep. 2023, doi: 10.3390/s23187819.

[51] X. Ma, X. Jia, C. Li, and C. Gong, "A sparse reconstruction method of physical field via multi-source sensors for flight vehicle," Aerosp. Sci. Technol., vol. 167, p. 110685, Dec. 2025, doi: 10.1016/j.ast.2025.110685.

[52] Y. Han et al., "Advanced Temperature Prediction for Electric Motors: A Review from Physical Foundations to Physics-Informed Intelligence," Machines, vol. 14, no. 3, p. 305, Mar. 2026, doi: 10.3390/machines14030305.