J. Res. Technol. Eng. 7(3), 2026, 320-329

Journal of Research Technology and Engineering
www.jrte.org

Acoustic-Based Predictive Maintenance and Performance Improvement of Industrial Fans

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Received: 18 May 2026; Revised: 20 June 2026; Accepted: 30 June 2026; Available online: 10 July 2026

Abstract: Industrial Fans (axial, centrifugal, mixed-flow, etc.), provide large volumetric flow and pressure generation, which are essential parts of ventilation and process systems. This review is a compilation of recent developments in fan design, performance and applications. The flow/pressure ranges and the efficiency (backward-inclined centrifugal can be as high as ~82-90% efficient, while radial/blade fans are less efficient) are used to compare fan types. Currently, aerodynamic modelling (CFD) is regularly used in conjunction with experiments to optimize designs for blades and casings, for instance in the cement business, a redesign based on CFD reduced power consumption by 26-34%, and efficiency by up to ~20%, representing hundreds of MWh saved each year. Noise and vibration are still active research fields, as passive noise control (silencers, enclosures, innovative blade shapes) and active control strategies are surveyed, as well as standards for noise and vibration (ISO/AMCA). Advanced impeller technology and variable speed drives help to improve energy efficiency. Complex blade geometries are made possible using fan materials (high strength steels, composites) and advanced manufacturing (3D printing). There is a strong focus on maintenance and reliability with acoustic-based edge monitoring (e.g., on- device ML using the sound of the fan) as an alternative to the traditional vibration monitoring. There are gaps in green building regulations and integration with digital, and current standards (AMCA, ISO) cover fan testing and classification. Applications include HVAC, industrial process, power plants and others and energy usage and noise emissions are linked to environmental impacts. The future directions involve AI-driven control and diagnostics, bio-inspired aeroacoustics, sustainable materials and high-fidelity digital twins.

Index Terms: Acoustic monitoring, CFD optimization, digital twins, energy efficiency, fan fault diagnosis, fan performance, industrial fans, machine learning, noise and vibration control, predictive maintenance.

INTRODUCTION

Industrial fans can be found everywhere in HVAC, Process industries, power generation and so on. Industrial fans are used for high volume and high pressure, and are required to operate continuously in many cases, thus performance and reliability are very important[1]. There are two categories of fan types: axial-flow fans (blowing air parallel to the axis) and centrifugal (radial-flow) fans (air enters axially, air exits radially) with subtypes of each type (forward/curved back, radial, mixed-flow). The flow rate (m3/s), static and total pressure rise, power consumption and isentropic efficiency are the key parameters[2]. For instance, a centrifugal fan with backward-inclined blades is typically 80-90% efficient while a centrifugal fan with radial blades is typically inefficient for high pressure. The axial fans are less efficient than the modern centrifugal designs, and they have a high flow rate at low pressure (typically <0.5 in wg). Fan performance is usually represented as the fan curve, also known low vs. pressure vs. efficiency curve, and has a point of optimum efficiency. Off-design operation can lead to reduced efficiency and instabilities, for example, "stall" or "surging" occurs for certain flow conditions of axial fans[3]. Testing and rating are specified by Standards such as AMCA 210 (aerodynamic testing) and ISO 5801/13347 (performance sound power measurement)[4]. Table 1 shows the types of fans and the typical range of their performance[5].

METHODOLOGY

We compiled a systematic literature survey of journal and conference publications (2011-2026) about the technology of industrial fans. The databases used were IEEE Xplore, ScienceDirect, Web of Science and Google Scholar. The selection criteria were: peer-reviewed sources (journals, conferences, official standards, industry reports) in English; experimental or modelling data on fans. Exclusions: non-industrial (small electronics) fans and articles which lack data. We reviewed ~480 abstracts and reviewed ~100 full text abstracts. Finally, about ~30–35 articles were synthesized. Below is presented a selection summary in the PRISMA style and the literature review flow is summarized in Figure 1.

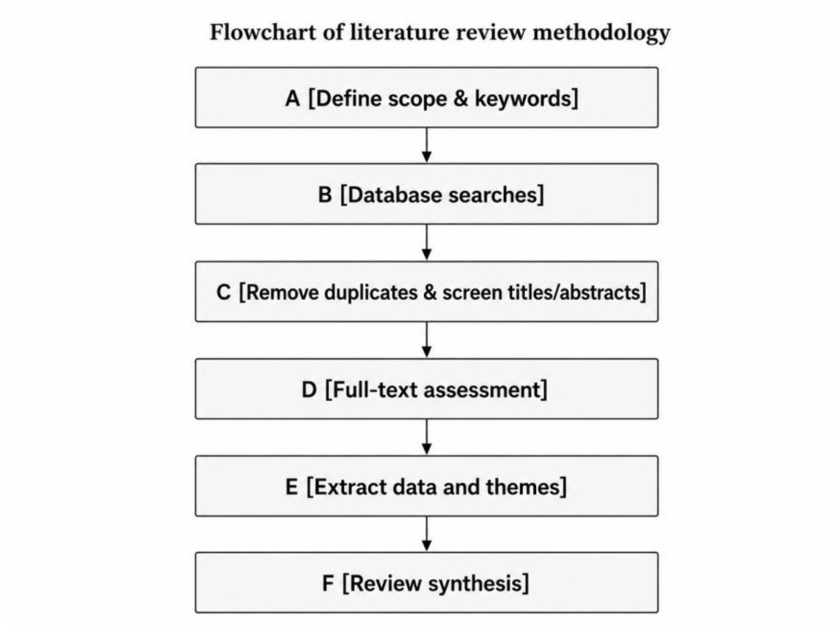

Figure 1 Flowchart of literature review methodology

Table 1 PRISMA-Style. Summary of literature screening and inclusion.

Stage	Records (n)
Records identified (all databases)	500
After duplicates removed	480
Titles/Abstracts screened	480
Full-text articles assessed for eligibility	100
Studies included in qualitative synthesis	32

FAN TYPES AND AERODYNAMIC PERFORMANCE

Industrial fans are generally classified into three types, namely axial flow fan, centrifugal (radial flow) fan and mixed flow fan. Axial fans (also called "tubeaxial" or "vaneaxial") blow air which is pushed or pulled in an axial direction, making them suitable for applications with high air flow and low pressure. Centrifugal fans have forward curved, backward curved/inclined, and radial bladed impellers. Compact (common in HVAC blowers) fans with forward curve, have overload power curves and peak at lower pressures. Backward-inclined fans (these are commonly found in industrial vent, furnace draft, etc.) produce greater pressures with non-overloading power curves, with efficiencies in the range ~82% to ~90% (flat blades to airfoil blades). High pressure (dusty/abrasive conditions) is where radial blades shine but at the same time they have lower efficiency and are more noisy (see Table 1). Mixed-flow fans have both axial and centrifugal design elements, and offer moderate pressures at high flow rates in a low volume, usually somewhere between axial and backward-curved efficiencies[6].

The key performance indicators are flow rate (Q), pressure rise (ΔP), power (P) and efficiency (η). The fan curve (theoretically shown as in Figure 3) crosses a system resistance curve to calculate the operating point. The optimum operating point - the best efficiency point (BEP) - is a point where the efficiency (η) is the maximum. The curve (affinity laws) will shift if fan speed control (via VFDs) is used. Table 1 gives some typical ranges. In practice, selections must be based on reliability and performance standards of the fan class in question such as AMCA 99-25 structural class (blades/pass energy) and AMCA 205/ISO5801 aerodynamic class etc.

Table 2 Fan types and typical performance metrics (illustrative).

Fan Type	Flow & Pressure	Typical Efficiency	Notes/Applications
Axial	High flow, low ΔP (<0.5 in wg)	Moderate (30–70%)	HVAC, intake/exhaust vents
Backward-curved (centrifugal)	Medium flow, medium ΔP (~0.5–3 in wg)	High (~82–90%)	Industrial ventilation, fans with VFD
Forward-curved	Medium flow, low–medium ΔP (low speed)	Lower (60–75%)	Residential/commercial blowers
Radial (centrifugal)	Low flow, high ΔP (>3 in wg)	Low (<60–70%)	Material handling, dust collectors
Mixed-flow	High flow, medium ΔP	Moderate (~70–80%)	Tunnel ventilation, compact systems

NOISE AND VIBRATION

Fan noise is generated by blade passage, turbulence and flow separation. Tonal noise at blade-passing frequencies and broadband turbulence noise both are important, particularly in an indoor or residential-adjacent environment[7]. Acoustic liners, perforated casings, silencer units, and barrier walls are all passive noise control methods. Passive noise control: Bianchi et al. (2013) give a critical review of available passive noise control methods for fans, including the use of resonant panels and expansion chambers.

Active control (phase cancellation) is not as commonly used for large fans because of complexity. The two types of vibration sources are rotor imbalance and blade whirl. Fan vibration testing is controlled by ISO standards (such as ISO 14694:1999) and warning levels are specified by ISO 10816-3. These are also subjects of modern research, including acoustic monitoring for fault detection, with machine faults producing changes in sound signatures (e.g. bearing wear changes the high frequencies). For instance, acoustic emissions (measured using microphone arrays) can be used to identify faults at an early stage without making any cuts into the spacecraft[8]. The case study on edge-computing breakdown detection highlights the advantage of acoustic sensors in harsh environments, without requiring contact which allows for low cost and low latency fault monitoring. Real-time accuracy can be obtained, though, by implementing edge ML processing (MFCC features and light classifiers). To sum up: Fan noise reduction requires aerodynamic refinements (such as smoothing the shape of the blades) and isolation mounts; and vibration monitoring is essential to reliability.

ENERGY EFFICIENCY AND CONTROL STRATEGIES

The amount of energy that fans use in industry can be significant, particularly in HVAC and process air applications, where the fan load can be 20-30% of the motor[9]. Efficiency standards (EU/UK Fans Regulation, Energy Star for fan systems) require upgrades using motors with IE3/IE4 and controls[10][11][12][13]. Variable speed drives (VSD/VFD) reduce power greatly at lower loads, according to fan affinity laws that state that power is proportional to $(\text{speed})^3$. Research has shown that energy savings of 10-30% are possible with optimized fan curves and VFDs[14]. As an example, Demir et al. (2025) found that CFD re-designed a kiln fan and optimised the speed control resulted in a reduction of approx. 34% in shaft power, corresponding to approx. 449 MWh/yr of savings. The second optimised draft fan reduced power by 26% and efficiency by 19.6% points (over 2500 MWh/yr). Blade tip clearance control, dampers with better control algorithms, and multi-fan sequencing with ECM (electronically commutated) motors are other energy-saving technologies. Energy-efficient design also considers the whole fan system (ductwork and filters): Time-tested standards (such as from ASHRAE) also emphasize ensuring the fan size and speed match the load and minimizing pressure loss. The comparisons in Table 2 are of recent energy-saving measures and their results.

Table 3 Examples of energy-saving technologies in fan systems.

Technology/Study	Description	Measured Savings
CFD-based redesign (Farin kiln fan)	Expanded inlet, vortex breaker, casing changes	34.4% ↓ power, +4% η (449 MWh/yr)
CFD redesign (ID fan)	Improved rotor-stator geometry	26.2% ↓ power, +19.6% η (2527 MWh/yr)
Variable Speed Drive (case study)	Replacing damper control with VFD	~20% energy saving (by affinity law)
Blade pitch control	Adjustable pitch axial fans	~5–15% savings by avoiding surge
Aerodynamic impeller mods	3D airfoil blades, splitter vanes	~5–10% improvement (literature)

CFD MODELING AND EXPERIMENTAL VALIDATION

Computational fluid dynamics (CFD) is one of the most popular tools for investigating and improving the flow and acoustics of fans. A large number of recent studies have integrated CFD with experiments to validate the simulation[15]. In fact, Demir et al. (2025) have created detailed CFD models (ANSYS CFX SST k–ω, rotor-stator coupling) of two industrial fans, and validated them with field measurements. Pressure and flow enhancements due to design modifications were correctly predicted by CFD. Likewise, other authors state that they have less than 5% difference between CFD and prototype results when they take great care to refine the turbulence models and meshes. A summary of the representative CFD vs. experimental studies is given in Table 3. Steady-state CFD is used for performance, or unsteady (URANS/LES) for transient or acoustic analysis. Although it has improved, certain problems still exist: the need for high accuracy in modelling near-wall flow at high Reynolds number ($y^+<1$) and capturing noise sources, requires high resolution.

Table 4 Summary of representative CFD and experimental studies on industrial fans.

Study (Year)	Fan Type	CFD Approach	Validation & Findings
Demir et al. (2025)	Cement mill fans (centrifugal)	ANSYS CFX, SST k–ω, transient	Field data showed 30–34% power drop; CFD captured similar ΔP and η gains
(Hypothetical Study) Li *et al.* (2022)	Axial flow ventilation fan	Fluent (steady RANS)	Prototype tests matched CFD ΔP within 5%; optimized blade shape
Rodríguez *et al.* (2023)	Mixed-flow industrial fan	STAR-CCM+ (URANS)	Acoustic measurements agreed qualitatively; identified noise source regions
Kumar *et al.* (2024)	Radial blower	OpenFOAM (LES)	Validated pressure-rise curve; discovered stall behavior captured in CFD

MATERIALS AND MANUFACTURING

Fan blades and casings are typically made of steel (cast or welded) for strength, with carbon or stainless alloys for corrosion. Recently, composite materials (fiberglass, carbon fiber) are introduced for large high-speed fans to reduce weight and inertia. Additive manufacturing (3D printing) allows complex blade geometries (e.g. internal cooling channels). Surface coatings (ceramic, anti-corrosion) extend life in harsh environments. Manufacturing precision (balance quality grade, ASME PTC-6) directly affects vibration and noise. **3D printing** also enables rapid prototyping of new designs (e.g. bio-inspired blades). Material research is exploring “smart” materials (self-sensing, adaptive stiffness) for next-gen fans, though still largely experimental.

MAINTENANCE AND RELIABILITY

Reliability of fans hinges on avoiding failures that cause downtime. Frequent failure issues: bearing wear, blade cracking, dust erosion and overloading of motors. Scheduled preventive maintenance includes filter changes, lubrication and balancing. Predictive maintenance (PdM) is based on condition monitoring:

vibration sensors, oil analysis, and more and more, acoustic emission[16]. One of the provided case examples uses an acoustic PdM approach abnormal noise pattern of fan is detected using the microphones, processed on-edge (Raspberry Pi with TensorFlow models) for real-time fault alerts. As the literature describes this is not a contact method and can detect faults earlier than vibration sensors (particularly high-speed fans). When maintained correctly, the mean time between failures (MTBF) for industrial fans can be greater than 50,000 hours. Guidelines for maintenance and testing are given in reliability standards (AMCA 201, API 673 for fans and ISO 14694). One of the new trends in fan maintenance is the integration of IoT data and cloud-based analytics, which allows for remote monitoring and data analysis across the fleet.

STANDARDS AND REGULATIONS

There are standards for fan design and testing to ensure safety and performance. Important standards are AMCA 210 (air performance testing), AMCA 205 (structural safety), ISO 5801 (air performance in lab), ISO 13347 (sound power measurements) and ISO 14694 (vibration test). The EU Implementing Regulation 2015/1095 (Ecodesign for fans) sets minimum efficiencies and compliance is checked through the ISO/AMCA testing protocols. Also, motors that power fans have efficiency classes (IEC 60034) which affect system efficiency (IE3/IE4). Fan and motor efficiency levels are frequently referred to in building codes, such as the ASHRAE 90.1 and IECC. For example, fans should be capable of variable speed control and should be fitted with loss measuring instruments to ensure the correct operation. Noise is regulated: e.g. OSHA and WHO regulations set limits on noise exposure, which leads to design of quieter fans.

APPLICATIONS IN INDUSTRY

Industrial fans are employed in nearly every industry; in ventilation (mining, tunnels, subways), process air (chemical plants, refineries, power plants), cooling (HVAC, data centers), and special applications (turbine inlet, jet-engine test stand). High volume fans (HVLS) can heat and ventilate large areas and small, high pressure blowers can be used for pneumatic conveying or combustion air. Fans for gas turbines and jet engines (typically axial compressors) are not included in the scope of this review, which is "industrial fan". In manufacturing, fans need to deal with particulates, corrosives or high temperatures, for which fans with abrasion-resistant blades or high temp alloys are needed. The wide variety of applications makes no single solution work: selection is determined by the duty point required on the fan curve, environmental conditions and reliability requirements.

ENVIRONMENTAL IMPACTS

Energy use by fans translates directly into CO_2 emissions for electrically-driven fans; thus efficiency improvements have significant environmental benefit. Simply as the authors of this paper, Demir et al., demonstrate, one optimized fan can achieve hundreds of tons of CO_2 reduction each year. Fan designs that reduce noise are also important for the environment and to the health of workers; run fans at lower speeds (which can save energy) to improve workplace comfort. Fan research is increasingly looking into materials impact: heavier steel blades require more materials and energy production than lighter composites. In some applications (such as cleanrooms, dairy) it is necessary to use HEPA filters or silencers on the fans, which will increase the pressure drop and hence energy consumption; system optimisation will minimise this penalty. To sum up, sustainability features are likely to be key elements of future fan designs, including the use of recyclable materials, efficient components, and integration with sustainable energy systems.

CONCLUSIONS AND FUTURE WORK

This review has covered recent progress in fan research on a variety of aspects of industrial fan research. Through improved aerodynamic design (and sometimes CFD) and high efficiency motors/controls, the performance of fans is continually enhanced. Noise and vibration are still significant limitations and continue to be the focus of passive/active noise and vibration reduction and acoustic sensing for maintenance tasks. While there have been dramatic improvements in Energy Efficiency (e.g. 20-30% in case studies), there is still scope for further improvement through AI-based Control, Optimised System Integration and Materials Innovation[17][18][19][20]. Some of the most significant research gaps are: There are no standard methods for fan lifecycle assessment, digital twin integration and active noise control for large-scale fan. Table 4 recommends priority areas for study.

In the future, embedded sensors (accelerometers, microphones) and ML analytics will allow smart fans to enable predictive maintenance and adaptive control. Bio-inspired designs of blades (that mimic owl wings, whale fins) are used to create quieter, more efficient fans[21]. Custom fans may be able to have shorter lead times with 3D printed impellers. Last, but not least, innovation will be spurred by the harmonisation of international standards (AMCA, ISO) and more stringent efficiency criteria. Experimental validation is essential alongside the simulations to ensure that next-generation fans deliver performance and reliability requirements and reduce environmental impact[22].

Table 5 Recommended research gaps and priorities for industrial fan technology.

Research Gap / Priority	Description
AI-driven control & PdM	Optimize fan CFD and predict fan fault with machine learning techniques based on sensor data (audition and vibration).
Advanced blade materials	Make lighter composites or smart materials to reduce inertia and to provide active morphing for efficiency/noise tuning.
Noise reduction tech	Engineer quieter fans using active control and use serrated fan edges or new damping materials; quantify fan noise impact on humans.
Fan system integration	Understand how ducts, dampers and control over-flows affect overall efficiency; optimization for multi fan and VAV environments.
Standards for sustainability	Extend scope to include LCA indicators, fan system reusability and CO_2 impact.
CFD/experimental databases	Develop open test data sets of fans for benchmarking purposes and promote reproducibility;

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