Advances in Ice Accretion Thickness Measurement Techniques for Aircraft Wing Icing Tests (Postprint)

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Abstract

The deterioration of lift-drag characteristics of aircraft wing surfaces due to icing directly threatens flight safety and has consistently been a hot topic in the aviation field. To reproduce the wing icing process and analyze the mechanisms of wing icing and anti-icing/de-icing, conducting wing icing tests is essential. To quantitatively characterize ice accumulation thickness and morphology on wing surfaces in aircraft icing tests, researchers both domestically and internationally have conducted numerous fruitful studies on measurement methods. This study systematically reviews the wing surface ice thickness and ice shape measurement methods and icing sensor devices proposed in recent years, classifies them into measurement methods based on physical principles such as direct observation, resonance, optical, electrical, thermal, waveguide, and hybrid methods, briefly introduces the design principles, advantages and disadvantages, and applicable scope of each method, aiming to provide a useful reference for the technical development of aircraft wing icing tests and anti-icing/de-icing system design.

Full Text

Preamble

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Advances in Research on Ice Accumulation Thickness Detection Technology in Airfoil Icing Tests

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Abstract: The deterioration of lift-drag characteristics of aircraft wing surfaces caused by ice accumulation directly threatens flight safety and has long been a critical concern in aviation. To reproduce the wing icing process and analyze the mechanisms of icing and anti-icing/de-icing, conducting wing surface icing tests is essential. To quantitatively characterize ice thickness and morphology in aircraft icing tests, researchers worldwide have developed numerous effective measurement methods. This study systematically reviews recently proposed methods for measuring ice thickness and shape on wing surfaces and icing sensor devices, classifying them according to physical principles into visual, resonance, optical, electrical, thermal, waveguide, and hybrid methods. The design principles, advantages, disadvantages, and applicable scopes of each method are briefly introduced, aiming to provide a useful reference for the technical development of aircraft wing icing tests and anti-icing system design.

Keywords: ice thickness; ice sensor; thickness measurement; icing test; technology review

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Introduction

Aircraft frequently encounter clouds containing supercooled water droplets during flight. When wing surface temperatures reach -10°C to 0°C [1-2], ice accumulates on the aircraft surface. Changes in external shape and surface roughness significantly degrade the aircraft' s lift-to-drag ratio [3-4], affecting stability and controllability. From the perspective of climb rate, range, endurance, and maximum speed, even light to moderate icing typically leads to performance degradation [5]. Furthermore, when ice fragments enter engines, they can damage the aircraft and endanger pilots and passengers. When windshields and radomes ice over, they obstruct pilot vision and affect communication signals. Ice formation on leeward surfaces may also prevent retraction of movable slats and flaps. According to FAA statistics, 380 aviation accidents worldwide between 2003 and 2008 were caused by icing [6-7]. The aviation industry considers aircraft icing one of the six major factors affecting flight operations, and NASA regards it as a priority prevention issue. Both FAA and NASA have expressed the need to expand icing databases [8-11].

Aircraft wing icing tests primarily include icing wind tunnel tests and natural icing flight tests, which are currently the most scientific and efficient methods for simulating aircraft icing conditions during flight [12]. Icing wind tunnel tests simulate the meteorological environment of the airspace where aircraft icing occurs to reproduce actual flight icing conditions and measure ice thickness, location, and morphology on model aircraft. Natural icing flight tests involve test aircraft flying in supercooled water environments to accumulate ice. The results of aircraft wing icing tests provide references for designing anti-icing and de-icing systems, ensuring flight safety under adverse conditions such as rain, snow, and fog. Since ice is a transparent, colorless solid with reflective surfaces that melt easily, most optical instruments or thickness measurement devices are unsuitable for ice thickness measurement. Measuring ice accumulation thickness has become a difficult challenge in testing, with current approaches typically using ice detectors installed directly on aircraft surfaces or indirect measurement of ice shape after formation.

This study addresses the challenge of measuring ice thickness in aircraft wing icing tests by systematically reviewing ice sensors and common ice measurement methods from various fields [13-15], classifying them according to physical principles into visual, resonance, optical, electrical, thermal, waveguide, and hybrid methods.

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1 Visual Methods

1.1 Visual Observation

Visual observation is the earliest and simplest method used for ice detection. Observers directly or indirectly monitor whether ice forms on surfaces. The British Normalair-Garrett icing detection system [16-17] places a thin-wing probe highly sensitive to icing conditions in a position easily observable by pilots [18-19]. When pilots observe ice on the probe reaching de-icing standards, they activate the de-icing system to remove ice from the aircraft surface. The probe also includes a heating device for repeated use, and a bottom light enables observation during night and cloudy conditions. During domestic civil aircraft flight tests, circular scales are installed perpendicular to the wing surface, allowing ice thickness to be determined based on the ice surface position relative to the scale. This method provides clear observation without any electronic components, offering high reliability and simplicity, but with low precision and sensitivity.

The British Dunlop company developed a wet-running anti-icing system [20] that installs multiple temperature sensors directly on surfaces requiring protection. By detecting whether ambient temperatures meet icing conditions, the system estimates ice accumulation and continuously operates heating elements to maintain surface temperatures above water freezing temperature. This method consumes significant energy and wastes resources due to its inability to accurately detect ice thickness and conditions, and has largely been replaced by more advanced ice detection and removal methods.

1.2 Photographic Method

The photographic method captures real-time ice images after formation and processes them to measure ice thickness, representing an early three-dimensional measurement technique. FMC Aviation Components developed an icing detection system using filters to distinguish liquid water from solid ice based on reflected spectral signals, then identifies icing areas through image processing. Researchers Struk and Lynch from the Canadian National Research Council used photography and videography with NASA Spotlight software to conduct icing tests in the High Altitude Research Test Facility (RATFac), measuring ice thickness and growth rates, as shown in Figure 1 [Figure 1: see original paper] [21]. In 1999, COLLIEŔ from Portsmouth University conducted similar research, as shown in Figure 2 [Figure 2: see original paper], achieving measurement accuracy of approximately $±$0.4 mm with high surface clarity after adjustments [22]. In 1997, ADDY used the photographic method to map ice shapes, as shown in Figure 3 [Figure 3: see original paper] [23].

Cross-sectional photography records ice cross-section profiles after cutting with a heated knife, similar to the hand-drawing method described below. While this reduces human error, the heated knife still destroys the ice shape and requires reference objects with established scales at measurement sections. Due to the transparent nature of clear ice, special treatment is needed before photography.

In 2007, Huazhong University of Science and Technology proposed a measurement method based on Sobel, LOG, and Canny operators. By photographing ice cross-sections to obtain boundaries and applying digital image processing techniques including filtering, edge detection, and edge connection, this method compensates for errors in edge extraction and distance adjustment, enabling accurate edge contour calibration and precise extraction of edge points to calculate ice thickness, thereby improving measurement accuracy and resolution [24-25].

1.3 Infrared Blocking Method

The infrared blocking method typically installs probes on the aircraft exterior [26]. When no ice exists between the infrared source and receiver, the receiver immediately receives the full infrared signal. With ice accumulation, infrared light passes through the ice layer to the receiver with reduced energy. Thicker ice causes greater energy loss and weaker received signals, gradually increasing voltage. This signal is transmitted to the processing circuit and then to the display. When ice thickness reaches a certain value, infrared light cannot penetrate the ice layer, the receiver detects no signal, output voltage peaks, and a signal is sent to the control circuit to activate the heater for de-icing, as shown in Figure 4 [Figure 4: see original paper] [18].

This sensor offers high automation and reusability but relatively low precision and sensitivity. Errors are significant during high-speed flight, though it can be applied to civil aircraft. The British company PENNY & GILES Aerospace Limited has already commercialized this technology [27].

1.4 Obstacle Method

The Lucas Mk3 series ice detector developed by British Lucas Aviation operates based on the principle that ice accumulation increases the resistance torque of moving components [28], as shown in Figure 5 [Figure 5: see original paper] [18]. The sensor' s upper part consists of a motor-driven rotating cylinder installed on the detection surface, with a circular plate exposed to supercooled airflow. When ice accumulates on the plate, it increases the cylinder' s rotational resistance torque. When the required torque exceeds the preset value, it converts to an electrical signal sent to the central control system. This method effectively detects ice presence but cannot quantitatively reflect icing severity, and suffers from short lifespan and low reliability.

1.5 Hand-Drawing Method

The hand-drawing method, also known as the hot-knife method, belongs to cross-sectional profiling techniques and digitizes aircraft ice shapes [29-30]. First, a selected cross-section is cut with a pre-heated metal sheet or hot knife along the wing normal direction to melt a groove. A pre-fabricated drawing board matching the wing leading-edge curvature is inserted into this groove to trace the ice boundary, requiring quick and careful operation to avoid melting or damaging the ice shape, as shown in Figure 6 [Figure 6: see original paper] [32]. The hand-drawn results are then measured, calibrated, and processed by computer to obtain two-dimensional ice shapes. Multiple cross-sections enable estimation of three-dimensional wing ice shapes. This simplest and most direct method is relatively common but produces rough results due to individual drawing habits, introducing errors during digitization. Ice shedding or melting during drawing [31] creates significant errors, and measuring multiple locations is labor-intensive and inefficient.

1.6 Casting Method

The casting method, developed in the 1970s, replicates three-dimensional wing ice shapes through molding [33], as shown in Figure 7 [Figure 7: see original paper] [35]. After icing tests, the wing model' s study area is immersed in liquid molding material at freezing temperatures to prevent ice melting and shape damage. Once the molding material solidifies, the wing model is removed and casting material with appropriate setting time and hardness is injected to obtain an ice shape replica. Comparing measurements between the casting and original model yields ice thickness values at various locations. This method requires good reproducibility of ice shapes, excellent low-temperature performance, and reasonable turnaround time [34]. While it can obtain complete icing conditions and thickness for the entire model, it is time-consuming, costly, and has limited application. It is rarely used for thickness measurement but often serves as a reference for developing new ice shape measurement methods due to its excellent reproducibility and complete documentation.

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2 Resonance Methods

2.1 Magnetostrictive Resonance Method

The magnetostrictive effect describes how ferromagnetic magnetostrictive materials elongate and contract along the magnetization direction in response to magnetic field changes, forming the principle of magnetostrictive ice sensors. The natural vibration frequency of magnetostrictive materials changes with ice accumulation, altering the excitation circuit' s resonant frequency to determine icing status. Eliminating stray vibrations improves process accuracy and prevents damage [36]. Harbin Engineering University developed such a magnetostrictive detection system, as shown in Figure 8 [Figure 8: see original paper] [37], primarily based on improvements to the Rosemount ice sensor.

Most commercial aircraft in North America carry Rosemount ice detectors [38], developed in the late 1960s for meteorological freezing rain detection and aircraft icing detection [39-40]. Through long-term use, testing, and data collection [41], it has evolved into a mature magnetostrictive sensor, as shown in Figure 9 [Figure 9: see original paper] [33]. The National Center for Atmospheric Research in Boulder, Colorado, has demonstrated its high sensitivity, rapid response, and accurate measurement in laboratory and wind tunnel studies. The Cloud Physics Research Department of Environment Canada verified accurate information transmission through analysis of data from 38 flights into winter storms [43].

2.2 Piezoelectric Resonance Method

Similar to piezoelectric flat-membrane ice sensors, piezoelectric resonance sensors exploit the functional relationship between the resonant frequency of sensitive elements and their stiffness and mass [44-46]. When ice forms on a metal diaphragm, it affects both stiffness and mass, with stiffness having a greater impact than mass. Thicker ice increases diaphragm stiffness and sensor resonant frequency [47-48], enabling ice presence and thickness determination through resonant frequency changes. A sensor developed by Huazhong University of Science and Technology, shown in Figure 10 [Figure 10: see original paper], achieves measurement sensitivity of 0.1 mm and a range of 0-2.0 mm [49].

In 1993, Finnair and Swiss Vibro-Meter jointly developed a clear ice detection system (CWAS), as shown in Figure 11 [Figure 11: see original paper] [50]. CWAS uses a diaphragm as its sensitive element that can be flush-mounted on aircraft surfaces. Both diaphragm thickness and stiffness can be controlled through manufacturing and material selection. Piezoelectric elements undergo physical changes under surface loading to power and maintain diaphragm resonance. Appropriate sizing of elements, diaphragm, and material properties keeps the piezoelectric element in resonant state. When liquid exists on the diaphragm surface, increased mass and changed stiffness significantly reduce resonant frequency. Frozen liquid thickness maintains a functional relationship with mechanical parameters of the diaphragm and frozen layer, detecting ice thickness from 0.2-10 mm with 0.05 mm accuracy, clearly distinguishing water from ice. It includes a temperature sensor (WITS) for auxiliary detection and can be heated for reuse [50-51].

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3 Optical Methods

3.1 Fiber Optic Method

Fiber optic ice sensors are significant for both aircraft ice detection and anti-icing [52]. In 2003, the UK pioneered fiber optic ice sensors that install flush with model surfaces, reflecting and transmitting infrared light to the measured surface. Without ice accumulation, infrared light enters the air directly and the internal receiver detects no reflected signal. With ice accumulation, light passes through the ice layer to the receiver, which transmits electrical signals to the control circuit to determine icing presence. This method can determine ice thickness and type based on optical properties of different ice forms. Later, a transmissive fiber optic sensor was developed that cannot be flush-mounted. Without surface ice, source light passes directly through receiving fibers to the receiver. With ice accumulation, light passing through the ice layer is attenuated, with only a small portion entering receiving fibers. By analyzing the mathematical relationship between received light intensity and electrical signals, surface icing and thickness can be detected, similar to the infrared blocking method, as shown in Figure 12 [Figure 12: see original paper] [53]. In 2022, Spain' s National Institute of Aerospace Technology (INTA) developed a fiber optic ice sensor with high accuracy and rapid response under rime ice conditions, though it struggles to provide reliable ice thickness values [53-54].

In 2009, Huazhong University of Science and Technology developed a dual-probe fiber optic ice sensor to address the inability of traditional fiber optic sensors to distinguish water from ice, using the effect of striped outer layers on fiber transmission capacity to differentiate solid ice from liquid water, as shown in Figure 13 [Figure 13: see original paper] [55]. In 2011, improved fiber optic reflective and transmissive detectors were developed using small circular, wedge-shaped, and rectangular fiber probes (Figure 14 [Figure 14: see original paper]) [56]. In the diagram, 1 is the transmitting fiber, 2 and 3 are receiving fibers with equal luminous flux. Background light and other interference are eliminated in subsequent control circuits, amplifying signals of the same magnitude. In transmissive detectors, fibers are made rectangular with infrared light reflecting and converting between circular and rectangular fibers. Reflective fiber sensors are sensitive to ice shape with high sensitivity and accuracy, but maximum measurement value does not exceed 3 mm, with many components and difficult manufacturing. Transmissive fiber sensors offer high sensitivity, maximum measurement up to 15 mm, simpler signal processing circuits, and lower cost, but are insensitive to ice shape with lower accuracy.

Unlike purely electrical strain sensors, the University of Cincinnati, Ohio, developed in 2000 a micro-electro-mechanical systems (MEMS) optical interaction device that integrates fiber optics and pressure sensors, better adapting to variable working environments than electrical devices. Processed silicon forms a pressure-sensitive diaphragm, with the silicon surface and glass-air interface forming Fabry-Perot cavity reflectors [57-58], protected by a reinforced housing that safeguards sensing elements and fibers transmitting light to the Fabry-Perot cavity. As shown in Figure 15 [Figure 59: see original paper], reflected light undergoes multiple reflections in the cavity before returning through the original fiber. This sensor combines advantages of fiber optic and pressure sensors, demonstrating good linearity, sensitivity, and response speed in tests, playing an important role in subsequent ice sensor development.

Fiber optic methods feature light weight, high accuracy, strong anti-interference capability, wide measurement range, small size, and good signal transmission performance as passive systems that can be flush-mounted without affecting surface flow fields. They can be installed in sensitive and dangerous wing areas, representing a major developing ice detection technology in aviation. Current research focuses on reducing size, enhancing wear resistance, extending service life, and maintaining sensitivity and accuracy.

3.2 Infrared Laser Method

Infrared light propagates through air and transmitting devices to infrared receivers, which convert light to electrical signals that are processed to display ice images reflecting measured object temperature and emissivity [60-61]. In 2009, EREN et al. [62] first proposed using infrared laser scanning to measure transparent objects like glass. Based on different penetration depths of infrared light in ice, water, and frost, Northwestern Polytechnical University developed an infrared laser point 3D scanning device for scanning iced model shapes and calculating ice thickness, as shown in Figure 16 [Figure 63: see original paper]. This device outputs 10.6 m wavelength laser, which penetrates less than 10 m in ice or water. It was later improved to infrared laser line scanning to address low point scanning efficiency [63], as shown in Figure 17 [Figure 63: see original paper].

This measurement approach offers extremely wide range, high sensitivity, accuracy, and speed, but only obtains object shape, requiring calculation to determine ice thickness with complex post-processing including point cloud registration and surface reconstruction. Swedish Science Company developed a road ice detector based on infrared spectroscopy [64], emitting infrared light to road surfaces and judging icing based on reflected infrared light. The device can distinguish various road conditions including ice and snow within 3-5 m of the installation point, as shown in Figure 18 [Figure 64: see original paper].

3.3 Laser Method

In 1998, the US disclosed a detector for ice, water, frost, or other solids using transparent media as sensing surfaces where solids or liquids can attach. A radiation generator emits focused radiation to one side of the medium, while a radiation receiver detects radiation from the other side, transmitting signals to receiving circuits to identify surface icing. The electromagnetic radiation can be visible light or other radiation [65]. Laser ice sensors utilize visible light optical properties, with sources emitting visible laser to detection surfaces. When ice accumulates on the surface, laser scattering, transmission, and reflection occur at fixed incidence angles. Without ice, receivers primarily detect scattered radiation. Differences in received light and reflection coefficients with and without ice determine icing presence and thickness. Due to clear ice transparency, surfaces are typically spray-painted before scanning to reduce transparency. Laser scanning configuration principles are shown in Figure 19 [Figure 66: see original paper].

Before measurement, ice surfaces can be sprayed with titanium dioxide-based developer. Northwestern Polytechnical University' s laser line scanning method uses sheet-light lasers to emit onto measured surfaces, with reflected light received by cameras recording laser stripes, as shown in Figure 20 [Figure 63: see original paper]. To address low reflectivity of clear ice surfaces, the method proposes frost treatment to enhance reflectivity. Based on the principle that laser line deformation correlates closely with distance and depth of field, measured object cross-sectional profiles are calculated. By changing relative positions between laser and object, complete 3D surface shape data is obtained, then processed through point cloud reconstruction and surface registration in Matlab to derive ice shape models and thickness data, with before-and-after images shown in Figure 21 [Figure 63: see original paper].

NASA' s Glenn Research Center demonstrated in 2014 that visible laser line scanning technology accurately and reliably scans ice shapes, with the Romer Absolute SI laser line scanner achieving 0.03 mm precision [67], as shown in Figure 22 [Figure 34: see original paper]. The Pennsylvania State University' s Adverse Environment Rotor Test Stand used the NextEngine ground-fixed laser line scanner with 0.13 mm precision [68]. However, to prevent noise from ice surface luminescence or errors from high laser transmittance in ice layers, surfaces require special treatment to reduce transparency before scanning.

Finland' s Visala company developed a laser ice sensor (DSC111) primarily for road detection, measuring objects 2-15 m from the installation point with water layer thickness 0-2 mm, ice layer 0-2 mm, and snow layer 0-10 mm, as shown in Figure 23 [Figure 64: see original paper]. The Goodrich-Scanmatic collaborative laser road ice sensor (LRSS) applies Goodrich' s aircraft ice sensor technology, distinguishing road attachments based on different optical characteristics and sensitive wavelengths [69], with detection results shown in Figure 24 [Figure 64: see original paper].

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4 Electrical Methods

4.1 Capacitance Method

Capacitance depends on electrode geometry and dielectric constant, which varies among different media [70]. When ice or water attaches to sensors, dielectric constant changes alter electrical signals, identifying media type. Since capacitance variation relates to medium thickness, the functional relationship between capacitance increment and medium thickness can determine ice type and thickness [71].

As early as 1998, Case Western Reserve University' s Microfabrication Laboratory proposed a MEMS-based capacitive ice sensor [72] using a micro-diaphragm made of borosilicate glass as the sensitive element with portable capacitance detection circuits. Proper protective packaging maintains pressure balance across the diaphragm, enabling resistance to severe icing conditions and operational reliability, as shown in Figure 25 [Figure 72: see original paper]. When voltage is applied between excitation electrodes and the diaphragm, electrostatic attraction deforms the diaphragm toward sensing electrodes, increasing capacitance. With ice attachment, diaphragm stiffness increases, raising voltage compared to ice-free conditions. Detecting electrical signal changes in the monitoring interface circuit connected to the diaphragm enables ice detection.

Taiyuan University of Technology' s capacitive ice sensor uses multiple parallel capacitors, distinguishing ice from water through different capacitance values, with temperature sensor assistance needed to differentiate water-ice mixtures. NASA' s patented ice sensor system includes two capacitive sensors (a and b) and a temperature sensor, as shown in Figure 26 [Figure 18: see original paper]. Electrodes are insulated to prevent false readings from conductive materials or electrolytes. Inter-electrode capacitance depends on geometry, spacing, and attached material dielectric constants, with capacitance values indicating water/ice presence and even ice thickness. Type-a sensors have grid structures with small inter-electrode gaps, detecting only thin ice layers. Beyond threshold values, sensor readings remain unchanged, representing the minimum detectable value. Type-b sensors have larger gaps with linear ice thickness response, reaching maximum values where further thickness increases produce no output change. Temperature sensors determine whether capacitance changes are caused by ice or water, measuring thicknesses of 0.5-1.5 mm with simple, cost-effective processes but low sensitivity and accuracy [73].

4.2 Strain Gauge Method

Traditional ice detection technologies are typically large and complex to install and assemble [74], potentially affecting airflow during aircraft operation. Therefore, small-size, high-sensitivity, embeddable MEMS-based ice sensors have become important research focuses in recent years [75].

The Institute of Electronics, Chinese Academy of Sciences, improved NASA' s capacitive ice sensor by designing a strain gauge ice sensor based on the piezoelectric and inverse piezoelectric effects discovered by Pierre and Jacques Curie in 1880, as shown in Figure 27 [Figure 76: see original paper]. RD detects flat membrane surface stress changes, RF is a reference resistor forming a dual-arm bridge with RD, and RM is an ice-melting resistor that activates immediately upon ice detection, heating to melt sensor surface ice. When the flat membrane ices over, increasing ice thickness deforms the membrane, reducing front surface tensile stress magnitude with thickness. RD detects maximum stress changes, converting them to electrical signals for calculating ice thickness after processing. The sensor' s flat membrane is only 60 m thick with sensitivity better than 0.1 mm. MEMS strain gauge ice sensors offer high sensitivity, easy detection, high reliability, simple manufacturing, flush mounting capability, but weak anti-interference capability [76].

4.3 Impedance Method

Goodrich Aerospace (formerly Rosemount) is a leader in developing and manufacturing aviation anti-icing and ice detection sensors. In 2003, they successfully developed and tested the Ice/No-Ice Sensor System (INISS) [77-78], as shown in Figure 28 [Figure 77: see original paper], primarily installed on wing leading edges for large-area ice thickness measurement. When water or ice attaches to sensors, impedance increases. Goodrich' s tests (Figure 29 [Figure 77: see original paper]) showed sensor measurement variation ranges can distinguish ice from other attachments, as shown in Figure 30 [Figure 63: see original paper].

These sensors can be installed integrally on wing leading edges with curved surface detection capability and customizable geometry for different measurement locations, completely preserving aircraft aerodynamic performance. They offer good sensitivity, detecting ice layers of 0.02-0.03 inches, though with relatively small detection ranges still under development.

A 2002 US patent disclosed an ice detector that determines aircraft surface icing and measures thickness through sensitive element impedance changes to control wing de-icing systems [79]. This method improves upon capacitive sensors' susceptibility to water effects without requiring temperature sensor assistance, reducing cost and simplifying circuits (Figure 31 [Figure 79: see original paper]) while improving reliability. Notably, its flexible geometry accommodates curved surfaces without affecting aircraft aerodynamic performance.

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5 Waveguide Methods

5.1 Ultrasonic Method

Two ultrasonic methods exist: pulse amplitude technique and pulse-echo technique [80]. Pulse amplitude technique uses piezoelectric ceramic crystals as transmitters, electrically excited to emit ultrasonic pulses to measured surfaces, with the same crystals receiving reflected echoes after returning to initial state. Without surface ice, ultrasonic energy loss in air is minimal, producing maximum received echo energy. With ice, some acoustic energy is transmitted and consumed by the ice layer, weakening received echoes and enabling ice detection, though without thickness information. Pulse-echo technique differs by transmitting sound waves within the ice layer using two piezoelectric ceramic crystals as separate transmitter and receiver. By measuring propagation time in the ice layer and combining with sound velocity in ice, thickness is calculated. This sensor measures ice thickness of 0.6-3.8 mm with 0.13 mm accuracy, light weight, high reliability, and can be installed on aircraft surfaces for real-time measurement.

In 1995, Finland invented an aircraft surface ice detector based on pulse amplitude technology [81], using a filamentary or ribbon acoustic waveguide transducer with an ultrasonic generator at one end and receiver at the other. The device includes electronics for measuring ultrasonic pulse intensity and attenuation through the transducer under icing conditions, simultaneously measuring resistance and electrically heating to melt surrounding ice for repeated use.

5.2 SH Wave Method

SH waves are shear wave components vibrating in-plane during elastic body vibration, measuring ice thickness through propagation characteristics in iced structures. They offer high sensitivity and small size, effectively detecting surface defects. Due to wave interference and diffraction characteristics, SH waves can bypass obstacles, propagate along surfaces, and travel long distances. Nanjing University of Aeronautics and Astronautics designed an SH wave-based ice sensor for rotor structures [82], using finite element analysis software for two-dimensional finite element simulation to verify sensor design feasibility.

Acoustic plate mode (APM) waves are elastic waves propagating in plate-like solid structures, typically referring to horizontally polarized SH-APM waves [83]. When propagating between input and output transducers, energy is confined between plate surfaces. Monitoring APM amplitude and phase delay changes between input and output identifies attached material types. For liquid detection using APM, interdigital transducers (IDT) can be deposited on one side of piezoelectric substrates with attachments contacting the opposite side, separating IDT from liquid while preventing significant APM attenuation. Studying characteristic frequencies of APM in free space and loaded liquids enables liquid attachment detection. Nanjing University of Aeronautics and Astronautics established a theoretical APM device model using COMSOL' s modal analysis module [84] to analyze frequency characteristics, achieving detection through characteristic frequency changes with liquid parameters, as shown in Figure 32 [Figure 84: see original paper].

Surface acoustic wave (SAW) is essentially SH-polarized guided waves with acoustic energy concentrated at the surface, making them much more sensitive to surface disturbances than bulk acoustic waves. IDT generates acoustic energy concentrated in thin sensor substrate layers, providing high mass sensitivity. Love waves, electromagnetic waves vibrating in the SH direction, are commonly used. Energy loss in ice is much greater than in water, distinguishing attached material types. Love wave energy concentration in thin layers makes them more sensitive to propagation characteristic changes than SH-APM or pure SH waves [85]. The US developed a MEMS ice sensor based on SAW methods, generating Love waves through interdigital electrodes deposited between substrate and surface [86-87]. Wave velocity changes and attenuation differences due to measured media' s inherent properties distinguish liquid water from solid ice. The Institute of Acoustics, Chinese Academy of Sciences, initially verified in 2008 that Love wave ice sensors can clearly distinguish attachments, as shown in Figure 33 [Figure 88: see original paper] [88-89]. SAW sensors are small, highly sensitive, enable wireless passive measurement, show clear differences in energy loss and frequency change between water and ice attachments, and maintain deterministic functional relationships with ice thickness for thickness measurement.

In 2002, Pennsylvania State University developed a wireless IDT ice sensor for remote ice detection, as shown in Figure 34 [Figure 90: see original paper] [90], utilizing SAW sensitivity to low-temperature environments where wave velocity changes enable continuous ice detection through properly designed micro sensors. SAW sensors offer high sensitivity but difficult manufacturing, and have not yet been widely applied in practice.

5.3 Microwave Method

Microwave ice thickness measurement includes microwave resonance and microwave emission methods [91]. Microwave resonance resembles magnetostrictive resonance: when ice or water accumulates on flush-mounted waveguide insulation layers, waveguide resonant frequency decreases with increasing thickness. Based on different effects of attachments on resonant frequency, functional relationships between resonant frequency and attachment thickness enable approximate ice thickness calculation with 0-25 mm measurement range. The aerial refueling aircraft Cessna Cruader 303 first carried this microwave ice sensor for testing, offering high resolution and ability to distinguish ice from other attachments. Microwave emission is typically used in marine ice detection, based on the principle that microwave radiation from ice is proportional to its thickness. Emissivity is primarily affected by ice/air and ice/water interfaces and ice thickness. Currently, microwave emission measurement accuracy and sensitivity are lower than visible and infrared data, providing poor precision for aircraft ice thickness measurement [92-93], though applicable to radome ice detection [94].

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6 Thermal Methods

6.1 Heat Flux Method

Heat flux sensors are primarily installed on aircraft surfaces to measure wide temperature ranges, from high-speed flight surface temperatures to temperatures in supercooled clouds [95]. When flying in supercooled clouds, temperature differences exist between inner and outer fuselage surfaces, creating internal heat transfer. According to Fourier' s law, heat flux gradients exist along normal wall directions during heat transfer, enabling developed steady-state and transient measurement methods for different operating conditions [96]. Heat flux signals are converted to electrical signals transmitted to control circuits for automatic de-icing when requirements are met, with ice quantity determined by comparing signals to ice-free conditions. In 2014, China Aerodynamics Research and Development Center developed a thermal resistance heat flux sensor based on this principle, as shown in Figure 35 [Figure 97: see original paper].

6.2 Latent Heat Method

Latent heat is the energy absorbed or released during phase changes. Latent heat ice sensors monitor the power required by heating wires to completely melt surface ice layers, operating in current pulse or constant temperature modes. Current pulse mode uses pulsed current to heat resistors. Without ice, temperature and resistance maintain specific functional relationships. With ice, melting ice changes resistor thermal characteristics, altering the temperature-resistance relationship. The degree of this relationship change determines ice accumulation and signals control circuits. Constant temperature mode continuously powers resistors to maintain constant temperature. When ice accumulates on resistor surfaces, melting ice absorbs heat, reducing surface temperature. To maintain temperature, resistors increase power, with power change magnitude indicating ice accumulation.

6.3 Balanced Bridge Method

The balanced bridge method uses temperature-dependent resistance changes, as shown in Figure 36 [Figure 18: see original paper]. The cylindrical sensor aligns its generatrix parallel to flow direction, containing two resistors connected via bridge circuits. The resistor parallel to flow does not participate in icing and serves for environmental detection, while the perpendicular resistor collects small water droplets from airflow. Without water droplets, both resistors have equal values. With water droplets, the horizontal resistor remains unchanged while the vertical resistor’ s surface insulation temperature changes, creating a functional relationship between resistance and surface temperature that unbalances the bridge. The difference between resistors indicates airflow water content, though temperature sensor assistance is needed to determine if the sensor is in a supercooled environment and whether ice forms.

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7 Hybrid Method

Individual ice sensors may produce false alarms in certain environments. Flat-membrane ice sensors, sensitive to mass changes, do not produce false alarms from minor disturbances. Combining two sensor types leverages complementary strengths. The Low Speed Aerodynamics Research Institute of China Aerodynamics Research and Development Center combined fiber optic and flat-membrane sensors, embedding them in a NACA0012 airfoil, as shown in Figure 37 [Figure 98: see original paper], achieving measurement times under 0.5 s and ice thickness range of 0.2-3 mm. This hybrid approach maximizes advantages of both sensors, compensating for weaknesses and showing good development prospects.

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8 Conclusions

Aircraft icing research forms the foundation for developing anti-icing systems, making accurate ice thickness measurement crucial in wing icing tests. Western countries began studying this technology in the 1920s, and after a century of development, ice detection technology across various fields has gradually matured. Rosemount’ s magnetostrictive ice sensor and Vibro-Meter’ s flat-membrane sensor offer high sensitivity and accuracy, with extensive flight experience accumulation making them mature and widely used. Emerging fiber optic and laser methods, despite some drawbacks, have proven feasible for ice detection through testing. Table 1 summarizes advantages and disadvantages of each method.

Methods are classified by quantitative/qualitative, online/offline, and destructive/in-situ characteristics in Table 2 .

Based on domestic research results, wing ice detection methods face challenges in simultaneously achieving high accuracy, wide measurement range, good wear resistance, and online measurement. To address these issues, future research should focus on four aspects:

1) **Selection based on installation location**: Choose the most suitable sensors for different aircraft structural features, ice characteristics, and sensor applicability at various locations to minimize flow field impact while maximizing accuracy.
2) **New anti-icing/detection systems**: Foreign development of airborne ice detection systems began in the early 21st century, aiming to detect and identify aircraft icing based on aerodynamic statistical characteristics and reconfigurable control to protect aircraft from hazardous icing. This should become a primary direction for domestic anti-icing system design.
3) **Hybrid detection**: Some detection technologies may fail in special environments. Using multiple sensors for hybrid detection with mutual verification can compensate for weaknesses and greatly improve measurement reliability, requiring researchers to select appropriate technology combinations based on actual operating conditions.
4) **Development of new detection methods**: Address fundamental technical issues using new materials, processes, and technologies to optimize existing methods and develop novel approaches, particularly for increasingly important fiber optic and laser methods where performance optimization is essential.

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Table 1 Comparison of Advantages and Disadvantages of Ice Accumulation Detection Methods

Physical Principle	Ice Thickness Measurement Method	Advantages	Disadvantages
Visual	Visual Observation	Simple design, high reliability, clear observation	Low precision and sensitivity, may affect flow field
	Photographic Method	High accuracy, real-time measurement, can distinguish water/ice, high resolution	Requires special treatment before clear ice photography, destroys ice shape during cross-section extraction
	Infrared Blocking Method	High automation	Large errors at high speeds, high energy consumption, low precision and sensitivity
	Obstacle Method	Effective ice detection	Cannot quantitatively measure thickness, short lifespan, low reliability
	Hand-Drawing Method	Simple and direct, can obtain 2D ice shape	Low accuracy, labor-intensive, low efficiency

Physical Principle	Ice Thickness Measurement Method	Advantages	Disadvantages
	Casting Method	Good ice shape reproducibility, complete ice shape and thickness data	Time-consuming, high cost, limited application
Resonance	Magnetostrictive Resonance Method	High sensitivity, rapid response, accurate measurement, accurate information transmission	Cannot quantitatively measure thickness, may affect test flow field
	Piezoelectric Resonance Method	High accuracy, distinguishes water/ice, flush-mountable, reusable with automatic heating	Small measurement range, requires temperature sensor assistance due to temperature sensitivity

Physical Principle	Ice Thickness Measurement Method	Advantages	Disadvantages
Optical	Fiber Optic Method	Light weight, high accuracy, strong anti-interference, wide measurement range, small size, good signal transmission, no flow field disturbance	Poor wear resistance, short service life
	Infrared Laser Method	High sensitivity, accuracy, speed, no test interference, obtains complete 3D surface data	Requires calculation for thickness, needs point cloud registration and surface reconstruction, complex post-processing

Physical Principle	Ice Thickness Measurement Method	Advantages	Disadvantages
	Laser Method	High sensitivity, accuracy, reliability, speed, no test interference, obtains complete 3D surface data	Requires calculation for thickness, needs point cloud registration and surface reconstruction, complex post-processing, requires surface treatment to reduce transparency
Electrical	Capacitance Method	Simple process, low cost, can distinguish water/ice	Low precision and sensitivity, limited measurement range
	Strain Gauge Method	Small size, high sensitivity, high reliability, simple manufacturing, no flow field disturbance, automatic de-icing	Weak anti-interference capability

Physical Principle	Ice Thickness Measurement Method	Advantages	Disadvantages
	Impedance Method	Distinguishes water/ice, high sensitivity, no flow field disturbance, flexible geometry, simple control circuits	Small measurement range, still under development
Waveguide	Ultrasonic Method	Light weight, high reliability, high accuracy, real-time thickness measurement, no flow field disturbance	Small measurement range
	SH Wave Method	High sensitivity, small size, long-distance propagation, wireless passive capability	Complex manufacturing, susceptible to environmental and temperature interference
	Microwave Method	Distinguishes water/ice, wide measurement range, no flow field disturbance	Low precision, limited application in icing field

Physical Principle	Ice Thickness Measurement Method	Advantages	Disadvantages
Thermal	Heat Flux Method	Wide temperature range, no flow field disturbance	Low precision, limited application in icing field
	Latent Heat Method	Automatic de-icing capability	Cannot provide ice thickness values
	Balanced Bridge Method	Can determine water droplet content in airflow	Requires temperature sensor to determine ice formation, cannot provide thickness values
Hybrid	Hybrid Method	Maximizes advantages of both sensors, complementary weaknesses	Currently limited use

Table 2 Classification of Ice Accumulation Detection Methods

Ice Thickness Measurement Method	Qualitative/Quantitative	Online/Offline	Destructive/In-situ
Visual Observation, Obstacle Method, Heat Flux Method, Latent Heat Method, Balanced Bridge Method	Qualitative	Online	Destructive (Hand-Drawing, Casting, Heat Flux, Latent Heat)

Ice Thickness Measurement Method	Qualitative/Quantitative	Online/Offline	Destructive/In-situ
Visual Observation, Photographic Method, Infrared Blocking Method, Hand-Drawing Method, Casting Method, Magnetostrictive Resonance Method, Piezoelectric Resonance Method, Fiber Optic Method, Infrared Laser Method, Laser Method, Capacitance Method, Strain Gauge Method, Impedance Method, Ultrasonic Method, SH Wave Method, Microwave Method	Quantitative	Online	In-situ (Magnetostrictive Resonance, Piezoelectric Resonance, Fiber Optic, Capacitance, Strain Gauge, Impedance, Photographic, Infrared Laser, Laser, Visual Observation, Infrared Blocking, Obstacle, Ultrasonic, SH Wave, Microwave, Balanced Bridge)
Hand-Drawing Method, Casting Method, Latent Heat Method	-	Offline	-

Note: Tables 1 and 2 have been reformatted for clarity while preserving all original content and method classifications.

Note: Figure translations are in progress. See original paper for figures.

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