Aircraft Icing Severity Evaluation

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Aircraft icing refers to the ice buildup on the surface of an aircraft flying in icing conditions. The ice accretion on the aircraft alters the original aerodynamic configuration and degrades the aerodynamic performances and may lead to unsafe flight conditions. Evaluating the flow structure, icing mechanism and consequences is of great importance to the development of an anti/deicing technique. Studies have shown computational fluid dynamics (CFD) and machine learning (ML) to be effective in predicting the ice shape and icing severity under different flight conditions. CFD solves a set of partial differential equations to obtain the air flow fields, water droplets trajectories and ice shape. ML is a branch of artificial intelligence and, based on the data, the self-improved computer algorithms can be effective in finding the nonlinear mapping relationship between the input flight conditions and the output aircraft icing severity features.

Keywords: aircraft icing ; aircraft safety ; computational fluid dynamics ; OpenFOAM ; machine learning ; da-ta-driven modeling

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Aircraft icing represents a serious hazard in aviation and has been the principal cause of several flight accidents in the past [1]. According to the International Civil Aviation Organization (ICAO), 42 plane accidents caused by icing are reported from 1986 to 1996, and 39% of them were fatal for at least one person [2]. When an aircraft encounters the supercooled water droplets that are naturally present in humid and cold atmosphere, a fraction of the supercooled droplets freezes upon the impact on the aircraft surface. The ice accretion on the wing's leading edge changes the original wing's shape and affects the aerodynamic performances. For example, the ice buildup on the wing decreases the maximum lift coefficient and increases the drag, which may cause instability and further lead to a crash [3]. Additionally, the ice accretion position is extremely important in evaluating the icing severity. For example, a small amount of ice at a key location might cause more severe performance degradation than a large amount of ice at a less important location. Therefore, evaluating the icing mechanism, ice shape and severity is of great importance to improving the flight safety.

Aircraft icing is an active research area and several approaches have been developed to investigate the ice accretion, including experimental study, numerical simulation and data-driven modeling. In terms of experimental study, NASA conducted a test flight and the testing data show that the effect of aircraft icing on the stability increases with the increasing angle of attack [4]. Papadakis et al. conducted experiments to study the effect of ice accretion on the aircraft aerodynamic performance and handling qualities at different icing times [5]. Wind tunnel tests have also been conducted to study the ice accretion process on aircraft, which provides valuable data of icing effects on aircraft stability [6].

Although experiments provide direct results and valuable information for icing mechanism investigation, carrying out the experimental study can be expensive and time-consuming; thus, with the building up of the theoretical icing models, more research has been focusing on the numerical simulation approach. To conduct the numerical simulation, the program that implements a mathematical model for the aircraft icing needs to be established. Then, the program can be run on a computer to obtain the icing results. Since the aircraft icing mathematical model is too complex to obtain the analytical solution, numerical simulation is essential to study the ice accretion process. For example, the LEWICE code [7][8], developed by the NASA Glenn Research Center, applied the Messinger icing model [9] to study the ice accretion for different flight conditions. FENSAP-ICE [10] implements a three-dimensional ice accretion solver which solves the Reynolds-Averaged Navier–Stokes (RANS) equation for airflow field and Messinger model for ice accretion. MULTI-ICE [11] achieves the functionality to compute ice accretion on multi-element airfoils. It applies a panel method for solving the aerodynamic field and Messinger model for icing computation. Cao et al. [12][13] established a numerical simulation method to predict the ice accretions based on the Eulerian two-phase flow theory. The permeable wall was proposed to simulate the droplet impingement on the iced surface effectively. Li et al. [14][15] developed the icing solver based on the OpenFOAM framework [16] to investigate the ice accretion process in a multi-shot manner; the icing solver is able to predict the ice shape as well as the effect of the ice accretion on the aerodynamic performance. Moreover, due to the highly modular structure of OpenFOAM, more features can be easily implemented into the solver. For example, the PoliMIce ice accretion modeling framework [17] was coupled with OpenFOAM to enable more accurate aerodynamics computation. Based on the computed airflow field, a generalized mass balance was introduced in PoliMIce to conserve the liquid fraction at the interface between the glaze and the rime ice types to achieve smooth transition between the two types of ice. In addition, surface roughness caused by ice accretion is also an important factor due to its effect on the heat transfer characteristics. For example, Fortin et al. [18] developed a thermodynamic model that combines mass and heat balance equations to the water states analytical representation to calculate the airfoil surface roughness caused by ice accretion. Han et al. [19] conducted experimental and analytical studies on airfoils roughened by natural ice accretion to improve the accuracy of current aircraft ice-accretion prediction tools. Recently, there have been studies focusing on predicting the flow field around the iced airfoil by using time-accurate methods such as detached eddy simulation (DES) [20]. Xiao et al. [21] improved the DES prediction of flow around airfoils with leading edge horn ice, which is important in studying the effect of ice on the aerodynamics.

In recent years, there has been growing interest in applying machine learning methods to aircraft icing research. It is motivated, on one hand, by the progress of artificial intelligence (AI) incorporating richer and/or more complex algorithms and, on the other hand, by the need of limiting the high computational cost of carrying out the numerical simulation [22]. AI is intelligence demonstrated by a computer program which has the ability to perform tasks associated with intelligence displayed by human beings. Machine learning (ML) is a branch of AI. Based on the training data, ML models are capable of addressing strong nonlinearity with the aid of constructing black-box input–output mapping [23]. Due to the complex interaction of multiple flight conditions, the mapping relationship between the input flight conditions and the output aircraft icing severity features is likely to be strongly nonlinear [24]; thus, ML has been implemented in several applications in aircraft icing to predict ice shape [25], icing area, maximum ice thickness, icing severity level [24][26] and the effect of ice on the aircraft aerodynamic performance [27]. The details will be given in Section 4. The accuracy of the ML models' predictions needs to be evaluated quantitatively by the error analysis method containing multiple statistical measures [23]. The trained ML models can make predictions based on any given flight conditions at a very fast pace. With reasonable accuracy, the built ML model has the potential to be an attractive alternative to the numerical simulation approach. Specifically, in aircraft icing, ML has a significant impact at three levels: for fast evaluating icing severity under different flight conditions, for estimating degradation of the aircraft aerodynamic performance by coupling with other computational fluid dynamics (CFD) codes and for increasing the flight safety by incorporating ice protection systems [26].

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