Development and Validation of Aircraft Icing Computational Simulation Code

Chengxiang Zhu
Key Laboratory of Fundamental Science for National Defense-Advanced Design Technology of Flight Vehicle, Nanjing University of Aeronautics and Astronautics, Nanjing, China

Chunling Zhu & Tao Guo
Nanjing University of Aeronautics and Astronautics, Nanjing, China

Lei Liu
AVIV Cheng Du Aircraft Industrial(Group) CO.,LTD, Chengdu, China

Abstract*—The purpose of this paper is to present some results on the development and verification of NUAA-ICE2D icing software code, which contains five separate program modules and a graphical user interface. Computational simulation of the ice accretion process on airfoils using multiple time-steps is studied in this paper. Firstly, all the modular codes for icing computation have been established in FORTRAN90 based on the Dynamic Link Library (DLL), and then a software package to perform normal functions of these modules has been developed using Microsoft Foundation Classes (MFC) framework. In addition, this icing software has some visualization tools that can help user analyze, explore and understand the simulation data. The architecture of the software, the functions of each component, its application to icing prediction and the further development are also discussed in this document. It is shown that all the modular codes of the software have good precision and fast calculation velocity during the process of grid generation, flow field calculation, droplet impingement calculation and ice growth analysis because of use of DLL and MFC, the illustration chart of operational interface is briefly shown in Figure 1. This platform software not only has established a reliable data communications law among these computational modules, but also has given an efficient way to predict the ice-layer accretion on the surfaces of geometry, the results are compared we are in accordance with the experimental data, shown in Figure 2. Once the calculations for ice accretion are activated, the software can call the five modules alternately and automatically in a robust way. This paper will provide some new techniques for predicting the ice accretion on airfoil efficiently and developing integrated icing software using mixed-language programming, which can be used in the stage of airfoil design and assessment. This paper presents some new ideas to improve the efficiency and reliability in icing calculations, especially in user-oriented way.

I. INTRODUCTION

When a plane flies through the cloud which contains many super-cooled droplets, ice accretion may occur on the front of wings, tail plane, and engine inlet. The ice contamination on the crucial surfaces can cause aerodynamic degradation and reduce the performance of lift components and engine. Computation and analysis of the ice accretion process on a full aircraft configuration and the resulting performance degradation have been undertaken by many researches. Results have indicated that the calculation of ice accretion, for the range of icing conditions required in FAR25 Appendix C, can be completed very well by means of improving the efficiency of icing calculation and advancing the stability and reliability of the icing code constantly[1].

Generally, the whole icing calculation should contain several separate program elements at least, they are:1)grid generation and reconstruction,2)the droplet trajectory and impingement calculation,3)the heat transfer process and ice growth calculation,4) the modification of boundary of the iced geometry, and 5)the analysis of aerodynamic characteristics and effects due to ice accretion[2,3]. The computational icing software can integrate all the relatively independent modules together so that the capability and efficiency of icing calculation can be enhanced greatly. Consequently the development of accurate, robust, well-documented computational software is a major function of the research activities in the icing branch.

In recent years, many departments in the world have been developing their own icing code or software, such as the National Aeronautics and Space Administration(NASA) in America, the Defence Research Agency(DRA) in British, the Office National d'Etudes et de Recherches Aerospatiales(ONERA) in France, and the Numerical Technologies International(NTI) in Canada[4-6]. All of the ice accretion codes at least consist of four modules for calculation of ice growth on a body subjected to icing conditions, these modules can generate the grid system for the geometry, calculate the flow field around the aircraft body, water droplet trajectories and impingement characteristics, analyses the mass and energy balance of water on the geometric surfaces.

NASA has developed a robust software code called LEWICE to study ice formation and growth. This code can reproduce results accurately for various spacing and time-step criteria across a computing platform which can runs on personal computers and Unix machines. The LEWICE has many different versions and the newest version is 3.0 released in January 2005. FENSAP-ICE is a three-dimensional complete, modular, and designed simulation system which can provide a useful tool to predict ice accretion. FENSAP-ICE can run on a wide variety of computer platforms, ranging from PCs and workstations to massively parallel machines. Of course, a graphical user interface (GUI) links all the computational modules seamlessly. However, the multiple time-steps can't be used in FENSAP-ICE because the grid reconstruction is very difficult in three-dimensional cases.

II NUMERICAL METHOD

A. General Frame of Icing Simulation Software

Based on the current situation of aircraft icing simulation and development of icing software, according to enterprises' development strategies and long-term research planning, this simulation software is designed to predict the ice growth on the geometric surfaces and evaluate the icing effects on the aircraft. This evaluation process can occur during many phases of the aircraft's design, manufacture, and operational lifetime. Therefore, the NUAA-ICE2D software developed by us is composed of the following five major components: element for grid generation, element for airflow field calculation, element for droplet impingement calculation, element for ice shape calculation, and element for geometry modeling, as shown in Figure. 1.

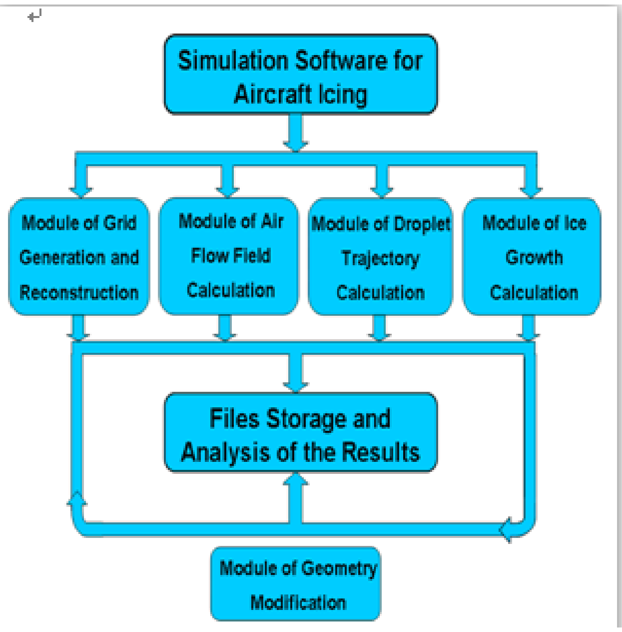

Figure 1. General frame of icing software

B. Module of Grid Generation and Reconstruction

The grid module is designed to generate a perfect grid system automatically around the model and redefine the iced geometry[7]. During generating the grid system, this module can generate a discrete approximation to the surface as faithfully as possible for a given number of points. Points are clustered in the area of lead edge of the airfoil. In addition, the clustered points can ensure geometry fidelity for the iced airfoil surface. An elliptic grid-generation method for finite-difference computations about airfoil configurations is used to obtain high-quality single-block grids.

C. Module of Flow Field Calculation

A two-dimensional Navier-Stokes algorithm is used to solve the stead or unsteady, uncompressible or compressible viscous airflow past an airfoil model. The model surface may become rough and flexural due to the ice accretion on the leading edge of airfoil. Therefore, the aerodynamic characteristic of airfoil should be calculated carefully. The flow solution is computationally expensive and time-consuming in every time step because of the severe transients that the flow solver must dissipate. In the procedure we have developed a high-efficiency method to generate a restart solution.

D. Module of Droplet Impingement

The droplet trajectories can be obtained by adopting a Lagrangian approach, which bases on hypothesis of no interaction of the droplet motion on the airflow field. The motion equations of super-cooled droplets are based on the assumption that the droplets are rigid spheres which is considered valid for smaller droplet diameter of less than 500 μm.

E. Module of Ice Growth

The growth of ice layer on the model surfaces refers to a complex fluid dynamics, heat transfer, and mass transfer process. The mass and energy balance is analyzed in each control volume to solve the fraction of freezing water along up and down surfaces of airfoil. The classical Messinger model is employed to simulate the process of the ice growth and the ice shape is obtained finally based on the mass and energy balance in each control volume.

F. Module of Geometry Modification

In the icing computation, surface modeling and grid generation for iced airfoils are a very challenging job, and the change of the geometry boundary is unpredictable in each time step [13]. Therefore, some functions like data probing, boundary smoothing, and structured grid refinement need to be done after every computational step of ice growth. The boundary smoothing function contains three steps, which are curve smoothing, discretization, and reshaping. The control features of NUAA-ICE2D not only can deal the iced surface successfully for the grid module, but also allow users to change some input parameters (e.g., smoothing angle, number of node set on the leading edge) and modify the geometry.

G. Programming Approach for NUAA-ICE2D Software

A Dynamic Link Library (DLL) is a file of code containing functions that can be called by other executable code (either an application or another DLL). We can use the DLLs to provide related codes that they can reuse and to parcel out distinct jobs. Unlike an executable (EXE) file, a DLL cannot be directly run, and DLLs must be called from other code that is already executing. The creation and use of dynamic link library can be found in all the calculation modules mentioned above, which are designed to further get high numerical stability and computational efficiency in the whole icing calculations. The details of the programming approach will be presented in the following section. There are many benefits by introducing the DLL files: Firstly, the code in a DLL is usually shared among all the processes that use the DLL; that is, they occupy a single place in physical memory, and do not take up space in the page file. Secondly, the source codes and the DLL files can be programmed separately from the space and time dimensions so that the coupling effects between them are largely reduced. Thirdly, the object code programs have smaller volume compared to the Static Link Library since the unique features in compiling and running programs have been used in Dynamic Link Library. This kind of approach, to great extent, can save the storage space and memory space in for users. Finally, it is more flexible for the programmers to change and revise the modular code by the way of separate DLL file. A FORTRAN source code distributed as a DLL will remain private (anyone cannot read the source code from the DLL file).

III RESULTS

A. The Implementation of Software

First of all, the software Package should be released into certain directory, and then the setup file can be activated by the user immediately. When the software installation is completed successfully, user can start up this software by clicking the coincident shortcut on the desktop. When the software is launched, all the functions required to compute a solution and display the results become accessible in NUAA-ICE2D through the interactive interface.

Now, we choose the 2D ice accretion module as an example, which includes an analytical ice accretion model and can evaluate the freezing process of supercooled droplets on airfoils. The atmospheric and meteorological parameters should be specified and input by the interface to determine the shape of the ice growth firstly. The illustration chart of operational interface is briefly shown in Figure 2.

The numerical simulation of ice accretion on NACA 0012 is performed under the geometric, aerodynamic, and meteorological conditions shown in Table 1. The output files from NUAA-ICE2D include information about pressure coefficient, collection efficiency, droplet trajectories, heat transfer coefficient, ice shape, distribution of surface temperature, iced boundary, lift coefficient, drag coefficient and so on. At each time-step, these files for all the results are stored in a new folder, so there will be seven new folders for the whole seven minutes calculations, these folders are established by the software automatically and named according to the local time. Based on the common conditions, the calculation results from NUAA-ICE2D for ice shape will be compared with the experimental results and other data taken from other icing codes, such as LEWICE in later paragraphs.

TABLE I INPUT CONDITION

Variable names	Symbol(unit)	Value
Angle of attack	c (m)	0.5337
Angle of attack	α (°)	4.0
Free-stream velocity	U∞ (m/s)	102.8
Free-stream pressure	P0 (Pa)	101325
Liquid water content	LWC (g/m3)	0.55
Median Volume Diameter	MVD (μm)	20.0
Static temperature	T0 (K)	265.7, 264.0
Time step	Δt (s)	60
Total time of icing	t (s)	420

B. Visualization of the Analysis Results

We present some results on the execution of NUAA-ICE2D icing software code. The functionality of the codes and the consistency of the output results are checked successfully using the input conditions shown in Table I. Various output results can be dealt and displayed on the software platform by clicking on the appropriate buttons. Visualization of the calculations allows user quickly to preview all the computational data by the expected way, as well as to analyze some complex data, and to communicate related results with the professional post-processing software, like TECPLOT software.

The following figures will show some results on the display windows of this icing software. In Figure 2 it can be seen that the water droplets trajectories are plotted very well for iced airfoil case. When one droplet is released at a distance of about eight chord length, its motion is controlled by local air velocity and related with the local time step. After a minor time step, the droplet moves from the old position to a new position which is determined by the control equation. In Figure 6 those red curves represent the droplet trajectories around the iced airfoil, and the green curve represents a computing trajectory at present. The dynamic display technology of the droplet's motion is applied to the software. Besides, there are other windows for displaying or drawing the results, such as aerodynamic data analysis (like Cl, Cd, Cm), drawing characteristic curves (like Cp, β, HTC, surface temperature, freeze fraction), and so on.

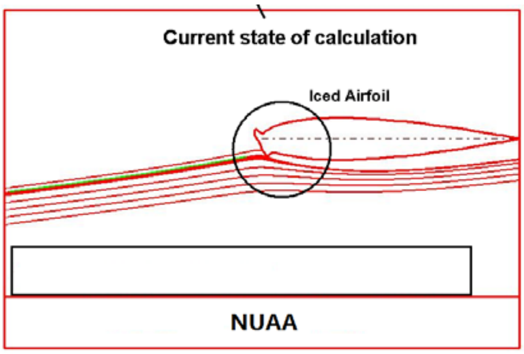

Figure 2. Interface for displaying the droplet trajectories

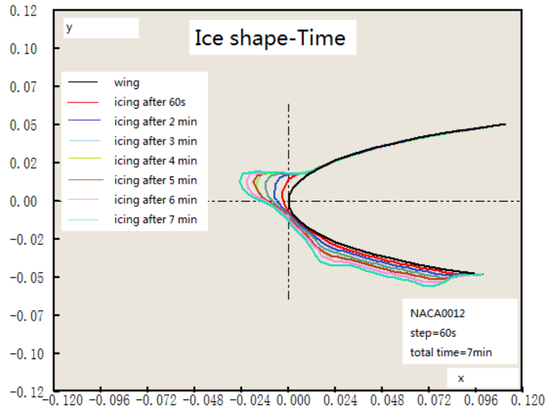

Figure 3. Results of Ice shape prediction for 2D airfoil

Figure 3 shows the results of the ice growth calculation, the total icing time is seven minutes, and the final type of ice shape is glaze ice because the environmental temperature is high. The growth of ice layer on the leading of airfoil is in the manner of time-step, which is set to be sixty seconds. Therefore, there are seven ice layers to indicate the process of ice accretion. Analogously, solution data of all the modules must be updated after every time step during the icing computation. As mentioned before, iced airfoil has complex boundary and the curvature is various along the leading edge. In the grid module, a fan-type grid around the 2D airfoil is created easily and can be used to generate the grid for the iced airfoil. Figure 5 shows the grid generator output for the iced airfoil, the orthogonality and node space are well controlled around the outer boundary of airfoil, especially in the region containing ice shape.

Figure 5 and 6 show the results of collection coefficient (β) and heat transfer coefficient (HTC) for the clean airfoil and iced airfoil. The label of x axial represents the surface distance from the geometry stagnation, and the s value in lower surface is negative. When the ice is not formed on the airfoil, these two characteristic curves are regular and smooth. However, as for iced airfoil, the collection efficiency distribution has some new features, such as multiple maximum values, decreasing impingement distance for droplets. The curve of heat transfer coefficient also becomes wiggly and is greatly influenced by the complex flow field around the leading edge due to ice shape. As can be seen, the up ice horn has a great influence on the heat transfer coefficient because the air velocity becomes higher compared with the un-iced condition.

Figure 7 and 8 show the comparison between the ice shape on NACA0012 airfoil calculated in this paper and the experiment data and LEWICE code computed results. It can be seen ice shape calculated in this paper are in accordance with the experimental data. And they are closer to experiment data more or less than LEWICE code computed results, especially in the aspect of prediction of freezing limitation, which illustrates that method of icing accretion software in this paper is feasible.

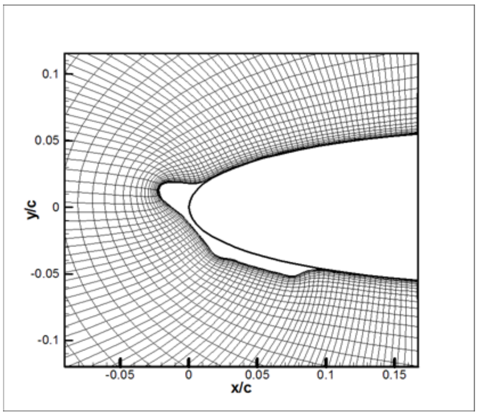

Figure 4. Grid for NACA0012 airfoil with ice shape

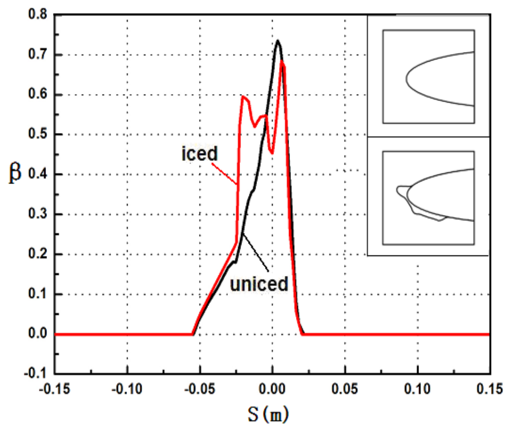

Figure 5. Comparison of collection coefficient

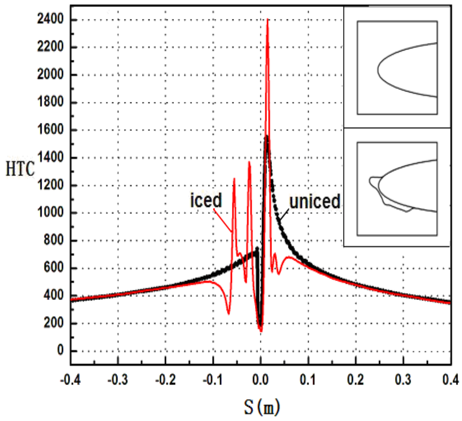

Figure 6. Comparison of heat transfer coefficient

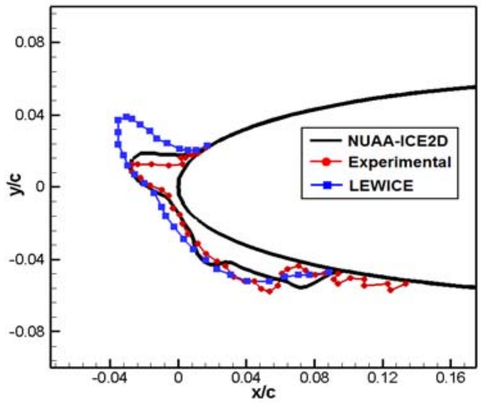

Figure 7. Comparison of ice shape at T=264K

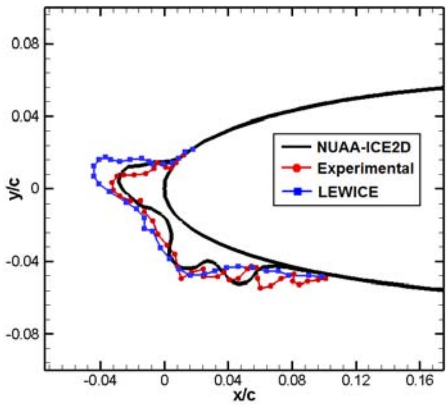

Figure 8. Comparison of ice shape at T=265.7K

IV SUMMARY

The details of NUAA-ICE2D icing software code are described in this paper. All the Modules in this software are programmed by high level language (VC++ and FORTRAN90), and the graphical user interface is designed based on the MFC framework, and the users are easy to understand and use. An introduction of the methods for designing and developing the icing software is also included. At last, one condition has been chosen to test the functions contained in the NUAA-ICE2D software, and the computational results demonstrate that the code has good reliability and efficiency in the process of icing calculation.

ACKNOWLEDGEMENTS

This work is supported by NSFC (No.11402114) and “the Fundamental Research Funds for Central Universities”, Nanjing University of Aeronautics and Astronautics basic scientific research projects for youth science, No.NS2014014.

REFERENCES

[1] C.Ghenai, C.X.Lin (2006) Verification and Validation of NASA LEWICE 2.2 Icing Software Code. Journal of Aircraft 43:1253–1258.

[2] David S.Thompson, Bharat K.Soni (2002) Automated Geometric Modeling and Grid Generation for Airfoils with Ice Accretion. In: Abstracts of the 40th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, 14–17 January 2002.

[3] Farooq Saed, Corentin Brette et al (2005) A Three-Dimensional Water Droplet Trajectory and Impingement Analysis Program. In: Abstracts of the 23rd AIAA Applied Aerodynamics Conference, Toronto, Ontario Canada, 6–9 June 2005.

[4] Guilherme Araujo Lima da Silva, Otavio de Mattos Silvares et al (2008) Boundary-Layers Integral Analysis - Heated Airfoils in Icing Conditions. In: Abstracts of the 46th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, 7–10 January 2008.

[5] Héloïse Beaugendre, François Morency et al. (2006) Development of A Second Generation In-Flight Icing Simulation Code. Journal of Fluids Engineering 128(2) :378-387, 2006.

[6] S.K.Jung, S.M.Shin et al (2010) Ice Accretion Effect on the Aerodynamic Characteristics of KC-100 Aircraft. In: Abstracts of the 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, Oriando, Forida, 4–7 January 2010.

[7] S.Nilamdeen, W.G.Habashi et al (2009) FENSAP-ICE: Modeling of Water Droplets and Ice Crystals. In: Abstracts of the 1st AIAA Atmospheric and Space Environments Conference, San Antonio, Texas, 22–25 June 2009.