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Choosing critical ice shapes on airfoil surface for the icing certification of aircraft

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Abstract

There is no explicit definition for critical ice shapes, and it is only mentioned in some ACs. Here, a rational and applicable definition for critical ice shapes is given based on well understanding of present literatures. Then, the available icing certification guidance concerning the various "critical ice shapes" is outlined. Different methods for determination of ice shapes as well as procedures are presented, and their characteristics are compared and analyzed. Based on the Combination Airfoil Assumption first presented by Glahn et al and developed by Farooq Saeed, we suggest a simple and useful method to determine the critical ice shapes on a normal airfoil which can be called combination airfoil comparison method. This method can be used to quickly get a preliminary ice shape for icing certification, but its criticality should be verified by other means of determining critical ice shapes. In order to examine the availability of this method, examples of Airbus aircraft types that have passed icing certification will be given. We hope that our findings and recommendations will be helpful to the applicant and icing certification team during aircraft icing certification.

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Keywords: Icing certification; Critical ice shapes; Airfoil surface; flight testing

1. Intruduction

Aircraft might encounter unexpected ice accretion on airfoil during flight, which is a big threat for the safety of flight. According to the statistic, 9% of significant safety accidents of aircrafts are due to icing. FAA and CAAC airworthiness authorities have established several airworthiness provisions (e.g.

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§25.1419, 25.1093, 25.1323(i), 25.1325, etc) related to safety of flight in icing conditions for civil aircrafts. The aircraft that only has to pass the icing certification by the airworthiness authorities can get the certificate of flying in icing weather conditions.

Nomenclature

Abbreviations

AC	Advisory Circular	AOA	Angel of Attack
CAAC	Civil Aviation Administration of China	CFD	Computational Fluid Dynamics
CIS	Critical ice shapes	FAA	Federal Aviation Administration
ICTS	Ice Contaminated Tailplane Stall	IPS	Ice protection system

During icing certification, dry-air flight testing with simulated critical ice shapes is an important campaign to show the compliance with the airworthiness regulations as well as to demonstrate the safely flying ability of the aircraft in icing conditions. This is partly due to the difficulty in obtaining critical ice shapes during a natural icing flight test campaign, but mostly for safety reasons.

As the pretesting of natural icing flight testing, dry-air flight testing serves three important purposes. One is to check the capability of the icing protection system (IPS) and its compatibility with other systems; the second is to demonstrate that the aircraft is safe for natural icing flight testing; and the last is to allow testing of shapes that may not be developed during a finite flight test program. Dry-air flight testing with simulated ice shapes are subsequently validated by comparison to test results in natural icing conditions or to tests on similar aircraft with similar geometries and systems. In order to fully validate the flight safety of operating in severe icing conditions that might encounter during flying, the ice shapes used in dry-air flight testing must be critical.

This work will go into detailed research of determining critical ice shapes on airfoil surface for the icing certification of aircraft, which mainly contains three parts: definition of critical ice shapes, methods for developing critical ice shapes and combination airfoil comparison method. Firstly, we have fully studied the current literatures including ACs and FAA research reports, and tried our best to give a rational and applicable definition for critical ice shapes. Then, the common used methods and procedures for developing critical ice shapes are presented, and their characteristics are compared and analyzed. We suggest a simple and useful method to determine the critical ice shapes on a normal airfoil which can be called combination airfoil comparison method. This method can be used to quickly get a preliminary ice shape for icing certification. In order to examine the availability of this method, examples of Airbus aircraft types that have passed icing certification will be given. We hope our findings and recommendations will be helpful for aircraft icing certification.

2. Definition of critical ice shape (CIS)

Ice shapes mean ice accretion geometries and features which include ice thickness, ice horn characteristics, and ice surface texture. The ice thickness refers to the height of the ice above the aircraft surface, as well as its location and its distribution on the aircraft surface. An ice horn is a distinctive protuberance of ice extending outward from the aircraft surface noticeably more than any surrounding ice. The horn's features include its length, its location on the aircraft surface, and its angle with respect to that surface, as well as its surface characteristics.

The word "critical" is used in FAA advisory material in various contexts. It generally indicates a condition or set of conditions most likely to be conducive to the largest adverse effects on a component or system. A more specific or explicit definition of critical ice shape, or methods to be followed in determining criticality, may not be provided. Only a general definition is provided in AC 20-73A[1] R.4 as following：A critical ice shape may be defined as the aircraft surface ice shape (formed within icing conditions defined by 14 CFR parts 25, Appendix C or 29, Appendix C) that results in the most adverse effects for specific flight safety requirements. According to this definition, there could be different critical ice shapes for different safety requirements.

Flying in icing conditions, the components of the aircraft on the windward side can be icing. Since the functions of the components are various from each other, the impacts of their icing are not exactly the same to the aircraft, so the necessary safety requirements will be different. According to the differences of icing locations and their impacts, the possible safety requirements may include handling and performance (Handling and flight quality, aerodynamic stability, stall characteristics. Icing on wings and tailplane), structure damaged and engine working influenced by shed-ice (ice shedding), performance of air data system (icing on air data system probes or sensors), visible range of windshield (icing on windshield), wrecking of protrusions such as antenna or risers (icing on protrusions), and so on. Among all these safety requirements, handling and performance requirements should be prior considered, while it is the ice shapes on the lift surfaces of the aircraft will influence the handling and performance of the aircraft.

However, structure damage and engine working influences mainly depend on the shed-ice mass, volume, density and hardness; effects on performance of air data system mainly depend on the blocking of sensor holes, or the coverage of probes; effects on visible range of windshield mainly depends on the icing area of the windshield; wrecking of protrusions mainly depends on the amount of icing on the protrusions.

Consequently, the factors that directly related with these safety requirements are not ice shapes which reflect ice accretion geometries and features. Only the effects on handling and performance are directly related with ice shapes. This is mainly because ice accretion on airplane wing will change the aerodynamic configuration, which will lead drag rise and lift loss, as well as decrease of critical AOA (stall AOA), and will further cause deterioration of handling of performance. The deterioration degrees are directly related with the distribution, geometry shape and roughness of the ice accretion.

AC 20-73A states, for large turbojet air transports with large thrust margins, ice shapes that are handling-qualities critical should be considered. Also consider conservative estimates of performance effects. All flight-testing should be performed at the most critical weight, center-of-gravity, flap, and gear configuration for the aircraft characteristic of interest. Modern transport category airplanes all adopt large thrust turbine engines, so it shows much importance to study critical ice shapes. According to the stating of AC 20-73A, we see that critical ice shapes should be validated by flight tests under the critical weight, center-of-gravity, flap, and gear configuration for the aircraft. Since the aircraft's handling of performance is very sensitive to ice accretion under the critical weight, center-of-gravity, flap, and gear configuration, we could conclude that the critical ice shape under the critical weight, center-of-gravity, flap, and gear configuration for the aircraft might be the aircraft's handling of performance critical ice shapes.

According to foregoing review and analysis of current guidance materials, we think that the effects of ice shapes are mainly on the aircraft's handling of performance, and the critical ice shapes are mainly the handling of performance critical ice shapes. "Specific flight safety requirements" mostly refer to the safety requirements of handling of performance. As a result, we draw a more specific definition of critical ice shapes as following:

Critical ice shapes are those ice accretions with representative geometries and features produced within the icing certification envelope，which can mainly result in the largest adverse effects on performance and handling qualities over the applicable phases of flight of the aircraft.

This definition is similar to guidance in ACs, but goes beyond, in that it focuses on ice accretion geometries and particular features which mainly contribute to criticality of flight performance and handling qualities of aircrafts.

Since there are too many parameters related to handling and performance, and usually, one ice shape might be critical for one parameter, while not critical at all for another parameter, applicant should take the key parameters and ignore subordinate parameters. According to literatures such as FAR-25 and AC 20-73A, etc., the "largest adverse effects on performance" refer to ice shapes and ice features which result in the largest loss in lift, the largest decrease in stall angle, the greatest increase in drag, and/or the largest change in pitching moment which may be realized under the certification conditions. The "largest adverse effects on handling qualities" refer to ice shapes and ice features that exhibit the greatest effects on the aerodynamics of aircraft control.

In the case of a control surface, ice accretion on the leading edge of a horizontal stabilizer, for instance, may be tolerable from the standpoint of lift and drag on the component; however, the ice accretion may diminish the effectiveness of the elevator. The ice that diminishes the elevator effectiveness most is the critical ice shape. This ice shape must be produced within the certification envelope and during the applicable phases of flight.

3. Methods for developing critical ice shapes

3.1. Considerations for developing critical ice shapes

Flight accident of Roselawn ATR-72 shows that just considering 45 minutes hold ice shapes is not sufficient [2]. Critical ice shapes should be considered in view of entire airplanes, and icing on protected surfaces and unprotected surfaces all should be taken into consideration, including the ice shapes due to IPS normal operating and fail operating. Specifically, it can be divided into the following 6 categories (see Table 1 as well):

- Delayed IPS activation,
- Runback ice shapes,
- Inter-cycle,
- 45 minute hold unprotected surfaces,
- Failed IPS while in a hold, and
- Ice Contaminated Tailplane Stall (ICTS) shapes.

Table 1. Ice shape categories and icing time for determining critical ice shapes.

IPS operating states	Icing conditions	Icing time /min
Normal operating	Ice due to delayed IPS activation	Exposing time before IPS effectively work (Ice detection + IPS activation + IPS effectively work)
	Runback ice	Icing exposing time
	Ice during internal deicing cycles	Deicing cycle intervals
	Ice on unprotected surfaces	45
	Ice Contaminated Tailplane Stall (ICTS) shapes	Icing exposing time
Failed operating	Icing on protected surfaces	22.5

Delayed IPS activation time is the sum of the time for icing detection, for pilots activating IPS and for IPS becoming fully effective. Unprotected surfaces exposure time in icing conditions takes 45minutes while IPS normal operating and holding, and this type of ices on the most critical unprotected main airfoil surfaces do not usually exceed a pinnacle height of 3 inches in a plane towards flight according to the service experience [3]; while IPS failed operating, the protected surfaces icing exposure time is from IPS failed working to complete leaving the icing conditions, which usually takes half time of the 45 minutes holding time. That is 22.5 minutes [1].

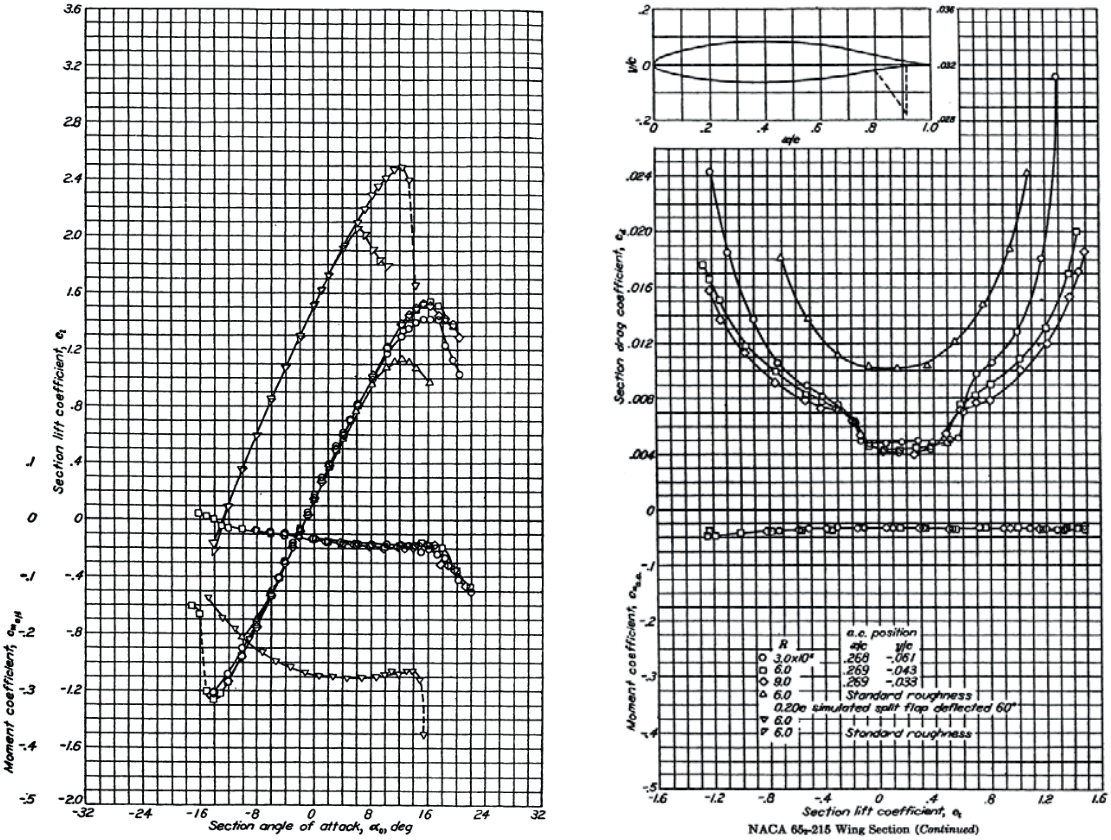

Fig. 1. Aerodynamic Effects of Standard Roughness (0.011-inch Carborundum Grains) for a NACA 652-215 Airfoil. (The Carborundum grains were uniformly distributed at a density of 5 to 10 percent of the area that extended from the airfoil's leading edge to 0.08c of the 24-inch model.) [4].

Concerning ICTS shapes, research result as Fig.1 shows that light roughness, such as that resulting from thin ice accretion on the leading edge of a horizontal stabilizer, may cause the horizontal tail to stall at a lower AOA (when compared with the uncontaminated tail)[4]. Flight-testing with "sandpaper" ice shows that the light roughness can be more severe than the larger critical ice shapes on some aircraft. Applicants should evaluate the acceptability of using the sandpaper ice during the certification program. During ICTS evaluation, ice shapes simulated by sand paper are attached to the tail flight surfaces and maneuvers including a zero-g pushover and cross controlled flight are performed to assess the sensitivity of the tail control surfaces to this type of ice formation. These maneuvers are performed at various speeds, power and flap settings. This assessment or testing requirement is a result of experience with in-flight icing problems in the field.

3.2. Common methods and procedures for developing critical ice shapes

The common procedures for developing critical ice shapes can be summarized by the following several steps (see Fig. 2):

(1) Predict the ice shapes of every flight phase and icing condition by using computation codes. And the predicted ice shapes are conservative ice shapes at this stage. The computational critical ice shapes are determined according to the maximum ice accretion rate. When the temperature of the icing surfaces is as low as the icing temperature, the critical ice shapes are determined according to the maximum water catch rate. Computation mainly aims at ice shape analysis of the lift surfaces (including wing, horizontal stabilizer, vertical tail and so on), or the protect surfaces and the unprotect surfaces. And then the predict ice shapes' adverse impacts on the flight are determined by pneumatic and vibration assessment; According to the degree of these adverse impacts, the roughly range of corresponding critical ice shapes is narrowed among the large number of calculation points.

(2) The computational critical ice shapes are further selected by dry-air tunnel tests. The force tests of the entire vehicle / parts / airfoil with simulated ice shapes are conducted to obtain the features of drag, lift, pitching moment, roll moments and so on; hinge moment tests of the entire vehicle or parts with simulated ice shapes are conducted to obtain pitching moments and hinge moments and the changes of the relationship between them. The results of adverse effects from tests and from computation/analysis are compared with each other to further narrow the range of critical ice shapes determined in Step (1).

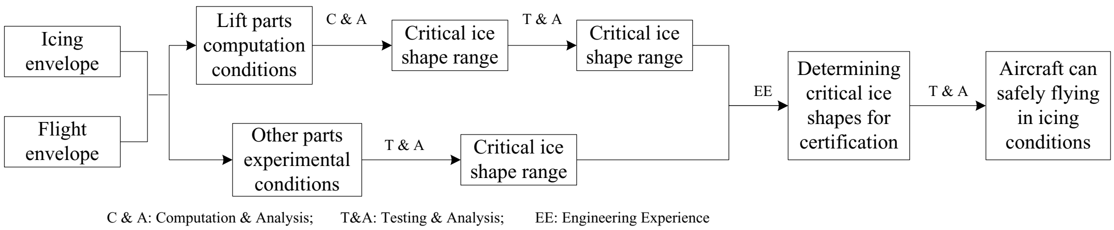

Fig. 2. Common procedure for determining critical ice shapes.

(3) Ice shape prediction by tests. For the case of complex three-dimensional shapes that the computer codes are very difficult to predict, or the calculation results are not believable, tests can be used to determine the ice shape, usually including icing tunnel test, simulated icing(by using water jet) flight tests and natural icing flight tests. Shrinkage ratio models are generally required in icing tunnel tests due to the restrictions on the size and test conditions. Combination shrinkage ratio model can be used to predict ice shapes during IPS normal operating. Simulated icing flight tests are usually used to determine the location and qualitatively determine ice shape characteristics, and mainly used for the lift surfaces ice shapes prediction. The natural icing flight tests here are carried out during the early icing certification to determine the ice shapes on non-critical parts, in order to prepare for flight tests with simulated ice shapes. Test is the most direct method for predicting ice shapes, but it is time-consuming and costly.

(4) The certification critical ice shape determination. Based on their own experience of engineering practice, applicants can consult with the certification department to determine ice shapes used in the icing certification as follows: choose a critical ice shape from the range determined in Step (2) and (3), and

make it applicable for all flight safety requirements and flight phases, which is the most critical ice shape; otherwise, a number of critical ice shapes should be selected and tested in dry-air flight test in order to validate the performance and aircraft handling qualities of the aircraft.

(5) Dry-air flight tests with simulated ice shapes and natural icing flight tests. Make simulated ice shape according to the ice shape chosen in Step (4), and conduct dry-air flight test to determine the critical ice shape effects on the aircraft's performance and handling qualities. Natural icing flight tests are conducted in the final stage of icing certification to validate that the shape determined in Step (4) is conservative, and to show that the aircraft can safely flying in icing conditions.

The general methods used to determine critical ice shapes can be divided into three categories: analytical methods, experimental methods and engineering empirical methods [5], Table 2 gives specific methods in each category and their characteristics.

Due to the complexity of determining critical ice shapes, applicants usually need to negotiate with certification department to determine one or a few critical ice shapes for airworthiness certification. Therefore, the determination of critical ice shapes eventually relies heavily on engineering experience. At the same time, some manufacturers can use accumulated experience in the past icing certification to build ice shape database, and use this database to choose critical ice shapes for new airplane types.

Table 1. Methods for determining critical ice shapes

Category	Name	Function	Application scope
Computation / Analytical Methods	Computation codes	Ice shape prediction	Lift surface icing tests
	Aerodynamic and flutter analysis	Effect s on performance analysis	Lift surface icing tests
Experimental Methods	Dry-air tunnels tests	Effect s on performance analysis	Lift surface with artificial ice shapes
	Icing tunnels tests	Ice shape prediction	Lift surface icing tests
	Airborne icing tankers tests	Ice shape prediction	Icing test for regional area
	Dry-air flight tests	Performance validation	Lift surface with artificial ice shapes
	Natural icing flight tests	Ice shape prediction and validation, performance validation	Entire airplane icing flight tests
Engineering Empirical Methods	Experience of icing certification	Determining critical ice shapes according to experience of similar types	Icing certification

1) The icing condition

Traditional method are based on maximum freezing rate or maximum water catch rate to determine the critical ice, and the freezing rate or water catch rate is associated with flight parameters and meteorological parameters. Regardless of the relationship between the parameters, the critical icing conditions have the following experience: total water catch rate, ① increases gradually with altitude increase; ② does not change with air temperature; ③ increases with the increase of water droplets size; ④ increases with the increase of flying speed.

2) Ice shape

Ice accretion features also influence the choosing of critical ice shapes. Ice accretion features mainly include ice types, ice thickness, surface roughness, and ice distribution on the surface of the aircraft, etc. For the calculation ice shapes on the wing and tailplane in holding conditions, the critical shape is often the shape on lift surfaces with the highest ice horn height. While choosing the tailplane critical ice shape, the trim condition that will make the lower surface to generate the most severe ice horn should be selected.

During the plane descending, the smooth and dense ice shapes may be taken as critical ice shapes. And deicing IPS or not fully evaporation heat type IPS surface, mixed ice or crystal ice can be treated critical.

4. Combination airfoil comparison method

When studying a specific airfoil icing characteristics, icing tunnel tests are usually used among the above methods. It is best to use full scale airfoil for icing tunnel tests due to the difficulties of ice shape generating and uncertainties of ice shape generating ratio. However, almost all icing tunnels in the world are very small for most of the airplanes, and cannot conduct full scale tests. In order to overcome this problem, Glahn et al have proposed an assumption for combination airfoil model, and Farooq Saeed et al have further developed this assumption [6] and finally acquired the conclusion: if the weather conditions, water droplets collision characteristics, the local flow fields of airfoil leading edge, geometric shape and roughness of the same model, thermodynamic properties are the same, geometric shapes of the airfoil models, roughness and thermodynamic characteristics of the surface of the models, are all the same, the ice shape generated on the full-size wing are same as the ice shape generated on the combination airfoil model. Harold E. et al [7] validated this assumption by a commercial airplane full scale airfoil and its combination airfoil icing tests, and conclude that the simplified combination airfoil can substitute for the full scale airfoil for ice shape research due to similarity of ice shapes generated on the both airfoils under the same weather conditions. As a result, we can see that if combination airfoil and full scale airfoil have the same leading edges, the ice shapes generated on them will be very similar under the same icing weather conditions. So, we can use the former combination airfoil to replace the full scale one to do the wind tunnel aerodynamic tests and theoretical calculations.

According to the assumption of combination airfoil and its validation results introduced above, this work proposed an airfoil leading-edge comparison method called combination airfoil comparison method based on the assumption of combination airfoil. We can compare the airfoil that to be studied with the airfoil with known ice shapes by overlapping their leading-edge points and chord lines, and compare their leading edge shapes, or compare their leading edge shapes with a little angle between the two chord lines. If their leading edges are coincident or very similar with each other, it is considered that same or similar ice shape will be formed on the studied airfoil as on the known airfoil under the same icing conditions. Thus, the ice shapes of the known airfoil can be used as the ice shapes of the studied airfoil to be used to conduct icing tunnel tests and theoretical computations. The advantages of this method are: (1) the known ice shapes and geometries will have fewer deviations with the true ice shapes; (2) the similar ice shapes might have enough research results can be referred to; (3) doing this not only can save a lot of money that would cost by test, but also can quickly get the ideal results. This method can be used to quickly get a preliminary ice shape for icing certification, but its criticality should be verified by other means of determining critical ice shapes. The following application example can validate the effectiveness and practicability of this combination airfoil comparison method.

Table 3. Characteristic data of Airbus A300B4-600 tailplane airfoil

Section	Span wise (%)	D/x, z	C/x, z	B/x, z	A/x, z	E/x, z
1	97.2	16, 53	-61, 84	-63, -4	-45, -52	22, -8
2	84.6	18, 59	-56, 89	-59, 0	-40, -49	25, -9
3	64.3	21, 71	-51, 101	-54, -7	-34, -55	32, -16
4	34.8	32, 93	-36, 122	-55, 4	-20, -52	36, -14
5	21.9	34, 105	-29, 130	-54, 8	-15, -47	37, -13

Literature [8] provides the wing and tailplane sections ice shapes of Airbus A300B4-600. Ice shapes of 5 along air-flow sections of the tailplane located at the position of 21.9%, 34.8%, 64.3%, 84.6% and 97.2% of the half tailplane-span are provided. These ice shapes are similar with the shape of Fig. 4 (64.3% position), lower ice shapes at the wing root, higher shapes at the wingtip. The change of ice shape height along the wingspan is 61~76mm. If the feature points of these ice shapes are connected, each of them can be simplified to a smooth polygon to replace the ice shapes provided in the literature. The feature points of these ice shapes are listed in Table 3.

Ice shapes of 4 along air-flow sections of the tailplane located at the position of 15%, 21.2%, 42.1%, and 100% of the half wingspan are provided. These ice shapes are lower at the wing root, and higher at the wingtip. The change of ice shape height along the wingspan is 35~72mm. These ice shapes are verified by icing flight test, and specific icing flight test parameters are listed in Table 4.

Literature [7] provides 4 section ice shapes located at the 23 %，47.8%，72.6%，97.4% of the half tailplane span, and the ice shapes are already simplified by connecting the feature points, and verified by icing flight test. The specific icing flight test parameters are listed in Table 5. Thus, Airbus company is using simplified ice shapes for icing flight tests in their airplanes' icing certification, which shows that the proper simplification of ice shapes will not cause the change of aerodynamic characteristics on the wing surface, and this can ease the manufacture of artificial ice shapes and CFD meshes and computations.

Table 4. Airbus A300B4-600 wing and tailplane icing test conditions

Flight parameters	Tailplane icing flight test	Wing icing flighttest
Flight phase	Hold	Hold
Altitude	17000ft	17000ft
Airspeed	230kts (calibrated air speed)	230kts (calibrated air speed)
Static temperature	-10℃	-10℃
Weight	100t	120t
Gravity center	31%	14.5%

Table 5. Airbus A321tailplaneicing test conditions

Flight parameters	Tailplane icing flight test
Flight phase	Hold
Altitude	17000ft
Airspeed	230kts (calibrated air speed)
Airfoil	Clean
Static temperature	-10℃
Weight	Maximum landing weight
Gravity center	Maximum front gravity center
Icing condition	JAR. Continues maximum

According to the above simplification principles, we have chosen the frequently used and researched NACA0012 airfoil ice shapes, A300 B4-600 airfoil ice shapes, and DH-6 tailplane ice shapes that NASA / FAA tailplane icing effect research group had selected, and taken the 4 airfoil ice shapes as the reference ice shapes to use combination airfoil comparison method. Then, we can get 4 ice shapes as shown in Fig.3~Fig. 6 for the great aspect ratio airplanes.

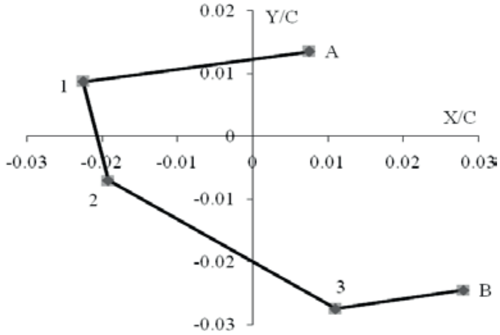

Fig. 3. A300 wing airfoil ice shape for great aspect ratio airplanes.

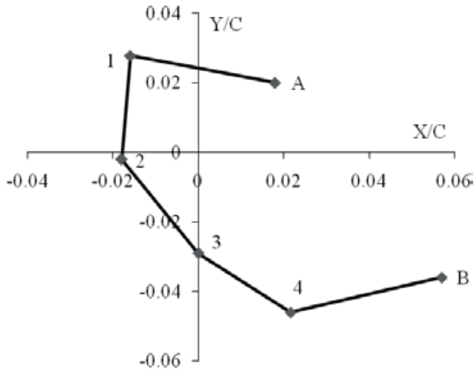

Fig.4. NACA0012 airfoil ice shape for great aspect ratio airplanes.

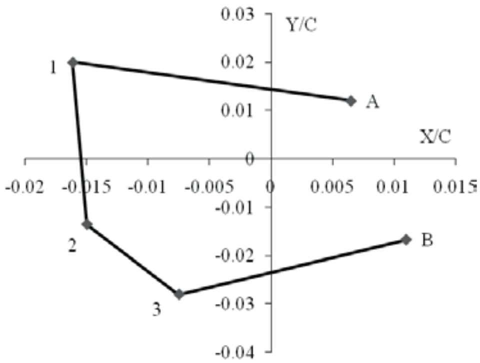

Fig. 5. A300 tailplane ice shape for great aspect ratio airplanes.

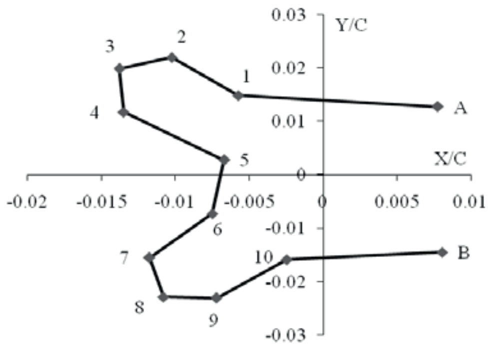

Fig. 6. DHC6 tailplane ice shape for great aspect ratio airplanes.

5. Conclusion

This paper goes into detailed research of determining critical ice shapes for the icing certification of aircraft, and gets the following results:

A rational and applicable definition of critical ice shapes are given as follows:

Critical ice shapes are those ice accretions with representative geometries and features produced within the icing certification envelope，which can mainly result in the largest adverse effects on performance and handling qualities over the applicable phases of flight of the aircraft.

Considerations and common used methods and procedure for developing critical ice shapes are presented. The characteristics of different methods are compared and analyzed. A simple and useful method called combination airfoil comparison method to determine the critical ice shapes on a normal airfoil is suggested. It can be used to quickly get a preliminary ice shape for icing certification. Examples of Airbus aircraft types that have passed icing certification is given to examine the availability of this method. Finally, several typical airfoil ice shapes for great aspect ratio airplanes are developed by using this method based on some known ice shapes data.

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