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Experimental Study of Unsteady Aerodynamic Characteristics of Transport Aircraft in Icing Conditions

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Abstract
Airframe icing causes significant degradation of aerodynamic characteristics and influences the flight safety. Wind tunnel study of longitudinal steady and unsteady aerodynamic characteristics of the transport aircraft in icing conditions is carried out in order to develop mathematical model of aerodynamics in the extended flight envelope. The wind tunnel results are validated through flight tests conducted for the real aircraft. Large glaze-horn ice shapes, corresponding to holding flight phase, are considered. Influence of an ice protection system as well as its failure is examined. The conducted study shows that the ice shapes of the holding phase leads to reduced stall angle of attack, maximum lift, and longitudinal damping.

1. Introduction

Enabling flight safety in the presence of adverse conditions, such as those caused by environmental factors, is a challenging problem. Analysis of accident and incidence reports revealed that the significant part of the weather-related accidents were due to aircraft icing. Modern rules of the aviation authorities (see, for example, [1]) require guaranteeing of flight safety of transport aircrafts in the icing conditions. There are several types of ice accretion scenarios concerning different flight phases, namely, takeoff (including the ground roll, takeoff, and final takeoff segments), en route, holding, and approach/landing (including both the approach and landing segments). Overview of the different icing effects on the static aerodynamic characteristics are given in [2].
Recently, a great efforts have been undertaken to develop aircraft control design tools and techniques for enabling safe flight in the presence of adverse conditions [2-5]. Most of the researches are aimed at studying the aerodynamic characteristics within the flight envelope. Nevertheless, modelling of the aerodynamics outside the flight envelope is crucial for improving the flight safety, but complicated with significantly nonlinear behavior at high angles of attack [6, 7].
This study is a first step in development of aerodynamics model of the transport aircraft in icing conditions for investigations of aircraft dynamics, including extended flight envelope. The present research is focused on experimental studying of the unsteady aerodynamic characteristic degradation caused by large, glaze-horn icing, corresponding to the holding flight phase. These ice shapes are taken into consideration since their relative dimensions are significantly large as compared to the other types. As reported by different authors [2, 5] influence of the large ice shapes on the aerodynamics can be evaluated using relatively small aircraft models. The other ice accretion scenarios are also have a great impact on the flight safety but require much more expensive experiments using large-scale models since the Reynolds number significantly influences on the results for such types of experimental simulations [2]. Results of flight tests obtained for a real aircraft were used in order to validate the wind tunnel results obtained with a small Reynolds number model. The additional attention is given to influence of an ice protection system on the aerodynamic characteristics during holding phase. Failure of the ice protection system is also examined. Contributions to degradation of the aerodynamic characteristics caused by the ice accretion on the wing and on the tail are studied.

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2. Experiment overview

The main purpose of the present study is to evaluate an influence of aircraft icing on the longitudinal unsteady aerodynamic characteristics of the short-range transport aircraft. The aircraft model is a low-wing monoplane with high aspect ratio wing, a conventional tail unit with a single vertical stabilizer and two wing-mounted engines. Corresponding Reynolds number is $\mathrm{Re} \approx 0.2 \cdot 10^6$. The aircraft model in the wind tunnel is shown in Figure 1. The model was mounted to a tail support strut. The basic geometrical parameters are given in Table 1.

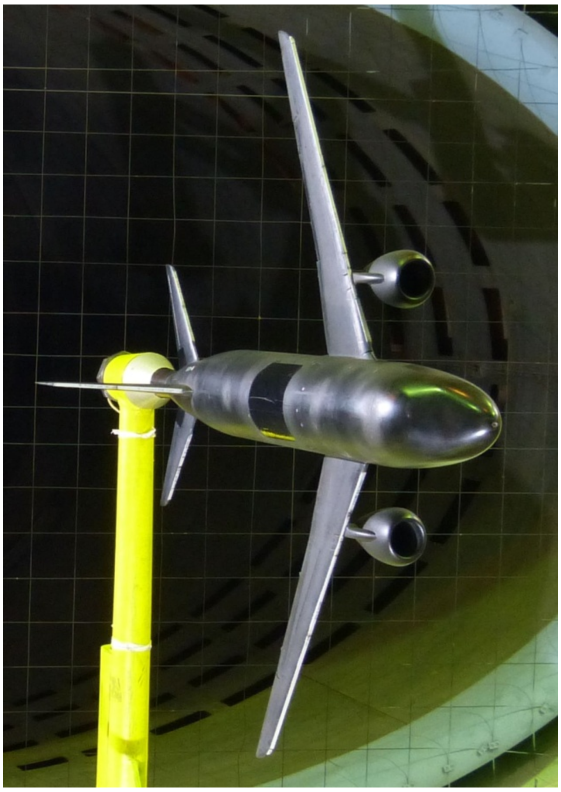

Figure 1. Fully iced aircraft model installed on the tail support strut in the wind tunnel test section.

Table 1 Basic geometrical parameters of the wind tunnel model

Dimension	Value
Wing Reference area, *S*	0.12 m2
Wing Aspect ratio	9.8
Wing Span	1.11 m
Wing Mean aerodynamic chord, c_{mac}	0.123 m
Wing quarter-chord sweep	25 deg
Dihedral angle	7 deg
Horizontal tail relative reference area	0.26
Vertical tail relative reference area	0.2

Experimental studies of unsteady aerodynamic characteristics of the transport aircraft configuration were conducted in TsAGI low-speed wind tunnel T-103.

The wind tunnel experiments were carried out in two stages. At the first stage, the static characteristics were studied. The incidence angle α was varied from -4 deg to 40 deg with the step of 2 deg. At the second stage, the dynamic derivatives were determined through a forced oscillation tests. Both types of the experiment were carried out both for the clean model and for the iced model. The wind tunnel flow velocity was $V_0 = 25$ m/s. Five component strain gauge balance located inside the model with reference center at 0.25 c_{mac} was used to measure the aerodynamic loads.

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While conducting the pitch forced oscillations the static derivatives $C_{N_\alpha}(\alpha), C_{m_\alpha}(\alpha)$ and dynamic derivatives $C_{N_{\bar{q}}}(\alpha)+C_{N_{\dot{\bar{\alpha}}}}(\alpha)$ and $C_{m_{\bar{q}}}(\alpha)+C_{m_{\dot{\bar{\alpha}}}}(\alpha)$ were obtained along with mean values of $C_{N_0}(\alpha)$ and $m_{z_0}(\alpha)$. The oscillation frequencies were *f* = 0.5, 1.0, and 1.5 Hz.

3. Artificial ice shapes

The present research is focused on studying the degradation of the unsteady aerodynamic characteristics caused by large, glaze-horn icing, corresponding to the holding phase and failure of the ice protection system during this phase [8]. Contributions to the degradation of the aerodynamic characteristics caused by the ice accretion on the wing and on the tail are evaluated in the experiment. These scenarios are taken into considerations since the relative dimensions of these ice shapes are significantly large as compared to the other scenarios. As reported by different authors [2, 5] influence of the large, glaze-horn ice shapes on the aerodynamics can be evaluated using relatively small aircraft models. The other ice accretion scenarios are also have a great impact on the flight safety but require much more expensive experiments using large-scale models since the Reynolds number significantly influences on the results for such types of experimental simulations [2]. In addition, a correct simulation of ice shapes, including roughness, can be very crucial while studying the stages with relatively small ice shapes (ground roll, takeoff, final takeoff segments, and etc.) This makes it very complicated to produce and install properly the ice shapes on the relatively small wind tunnel models.
Experimental studies of relatively small wind tunnel models require a high precision of manufacturing of the ice shape simulators. In the present research, the ice simulators were produced using the 3D printing.
Artificial ice shapes were placed on the wing, vertical and horizontal tail. Influence of the icing effects on the longitudinal aerodynamic characteristics were studied in the experiments when the artificial ice shapes were installed separately on the wing or on the horizontal tail. Icing of the vertical tail was not included in the study of longitudinal aerodynamic characteristics because of it small influence. In addition, the unsteady aerodynamic characteristics of the aircraft in case of failed ice protection system were also considered and compared with the results obtained for the properly working ice protection system. If the ice protection system working were considered, there were no ice shapes placed in the zones of heating, which were in the middle sections of the wing. In the failure conditions, in the heating zones, there were installed the artificial ice shapes that are smaller than the large ice shapes corresponding to the switch-off of the ice protection system. The scheme of ice-shape location are shown in Fig. 2.

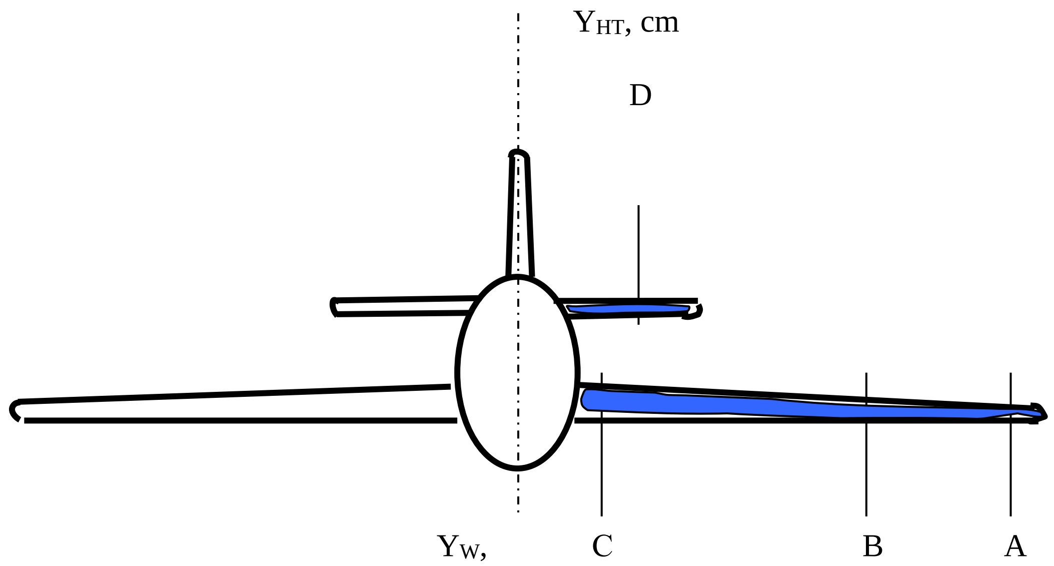

Figure 2. Scheme of location of the ice shapes.
Y_W and Y_{HT} are the sections of the wing and the horizontal tail. The artificial ice shapes for right side of the wing is symmetrical. The forms of the artificial ice shapes in sections A-D corresponding to the holding phase and of the artificial ice shapes in sections A and B corresponding to the failure of the ice protection system are given in Figure 3.

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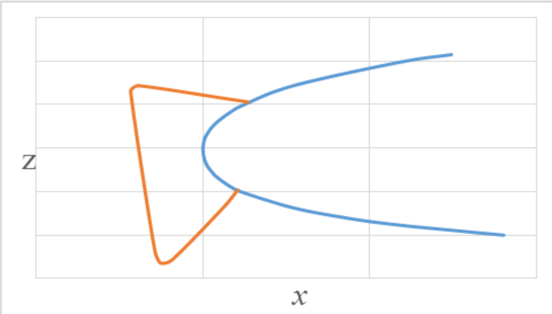
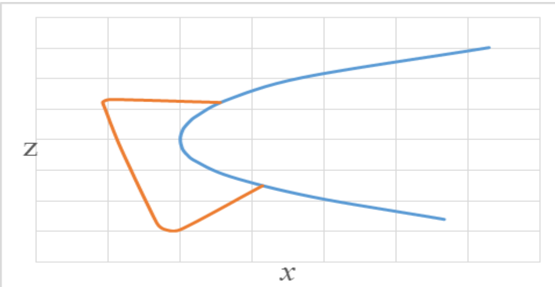


a) Section A



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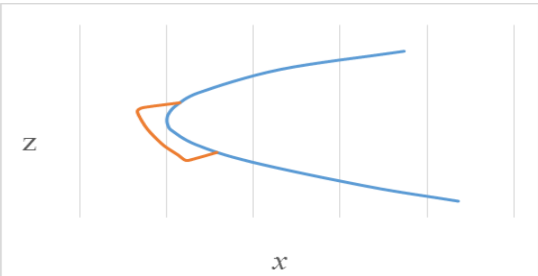
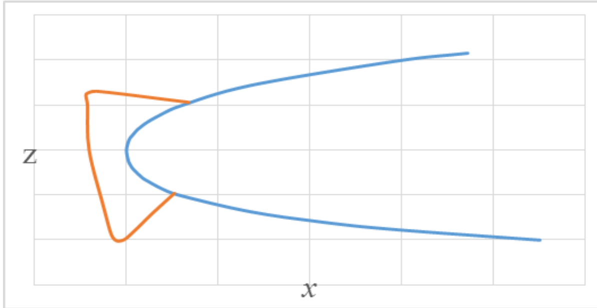
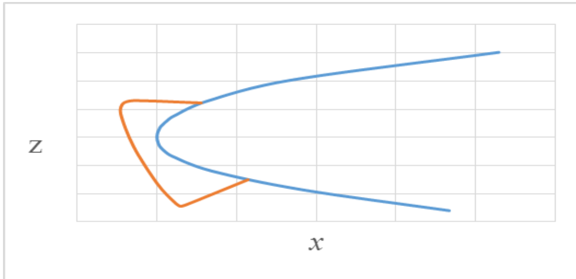


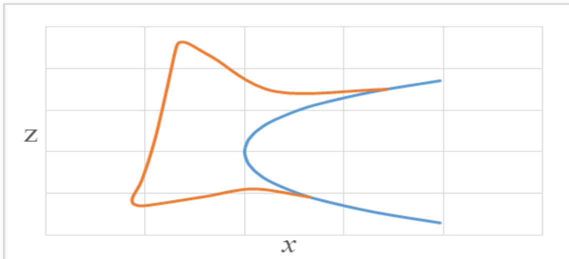
c) Section C



d) Section A: Failure of the ice protection system



e) Section B: Failure of the ice protection system



f) Section D: Icing of horisontal tail

Figure 3. View of artificial ice shapes

The artificial ice shapes were printed with the printing precision being 0.1-0.2 mm. The examples of the printed artificial ice shapes are shown in Figure 4 a. Photo of the model with installed artificial ice shapes corresponding to the holding phase are shown in Figure 4 b. One can see the artificial ice shapes are mounted on the wing and the horizontal tail.


a


b

Figure 4. Printed artificial ice shapes: a – examples, b – installed on the aircraft model

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4. Experimental results

4.1 Static tests

Static test results are given in Figures 5-8. Normal force and pitching moment coefficients are plotted in Figures 5, 7 and 6, 8 correspondingly.
The flight tests were also conducted for the real aircraft for the clean configuration and for the configuration with artificial large, glaze-horn ice shapes. The aerodynamic coefficients were identified using the transition processes obtained in maneuvers during a flight test phase. The results are given in Figure 6 and 7. From the comparison of the wind tunnel and flight test results one can conclude the following. Nevertheless, the results obtained for the wind tunnel aircraft model (small corresponding Reynolds number) and the real aircraft differ in significant way for the clean configuration, the results obtained for the configurations with artificial ice shapes (AIS) are quite similar. This gives us opportunity to evaluate the main tendencies of aerodynamic characteristics of the aircraft in presence of large glaze-horn ice shapes.
The curves corresponding to the clean model, the model with artificial ice shapes installed on the wing and HT, the model that has ice shapes installed on the wing and the HT separately are given in the figure 5. One can see that the curves of aerodynamic characteristics of the models with iced wing and the fully iced model are very similar. This coplotting gives us inside that the main contribution to degradation of the longitudinal aerodynamic characteristics, both for C_N and C_m, are caused by icing of the wing. Thus, the configurations can be divided into two groups, namely, the iced wing group that includes configuration with ice shapes at the wing and the fully-iced configuration and the clean wing group that includes configuration with ice shapes at the HT and the clean configuration. The results reveals that stall for the iced wing configurations is observed at the angle of attack that is two degrees lower.

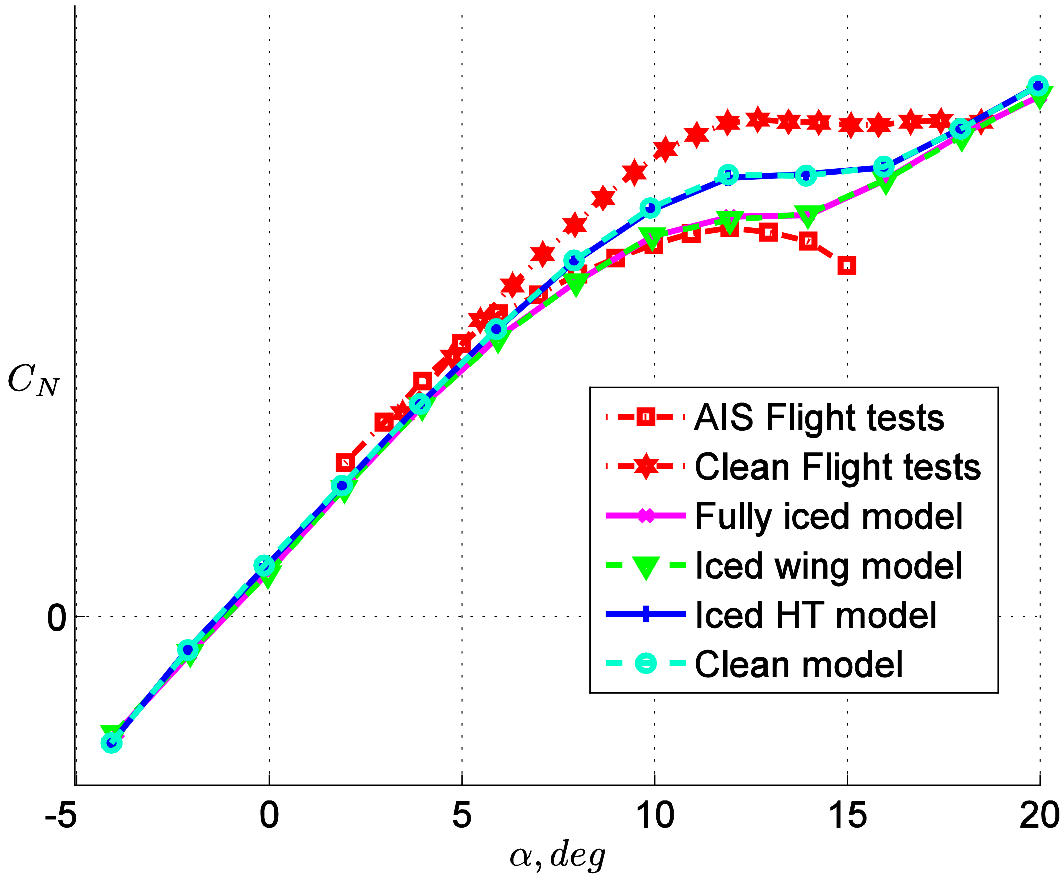

Figure 5. Normal force coefficient

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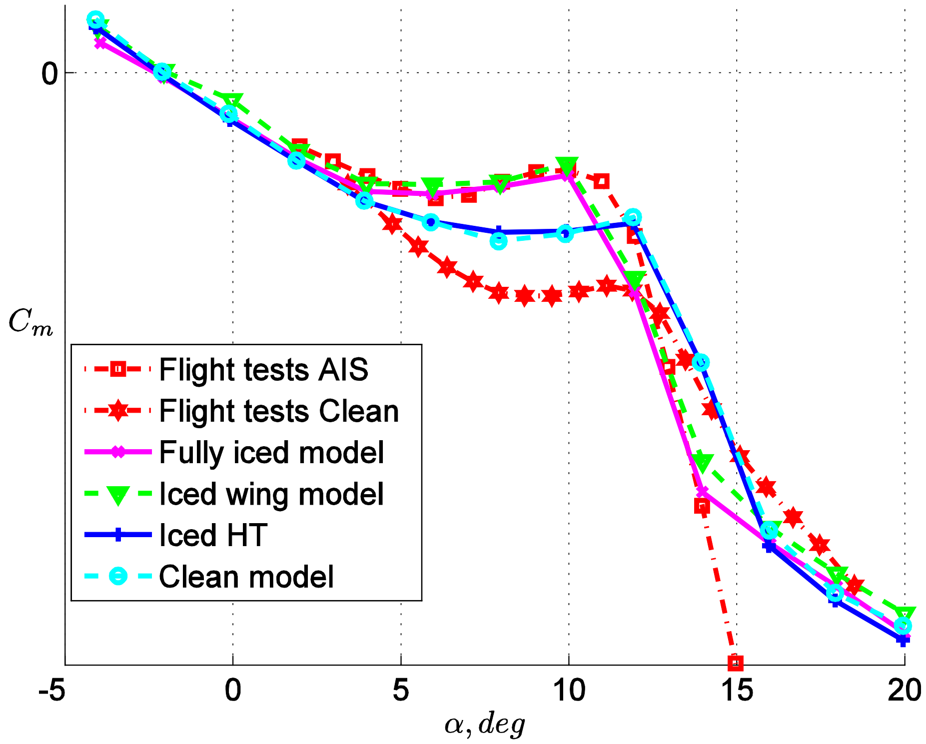

Figure 6. Pitching moment coefficient

Regarding pitching moment coefficient one can see that presence of the ice on the wing makes aerodynamic coefficients in the pre-stall region more nonlinear.

Influence of the ice protection system on the normal force and pitching moment coefficients was also studied. The results are given in Figures 7 and 8.

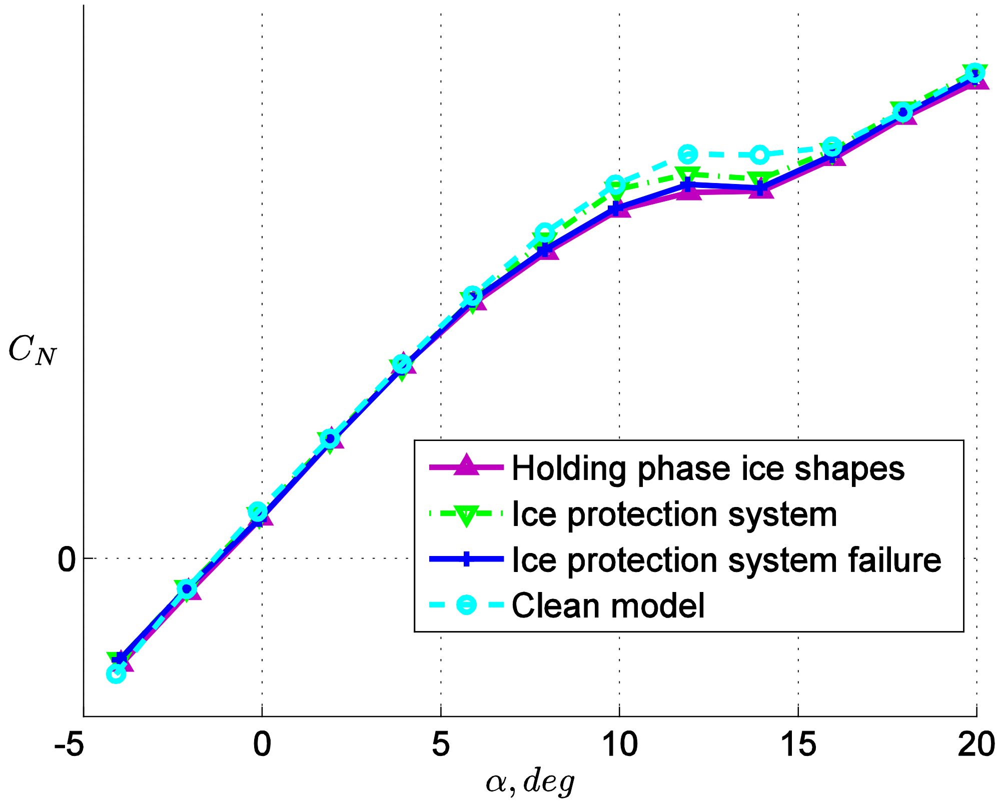

Figure 7. Normal force coefficient: ice protection system influence

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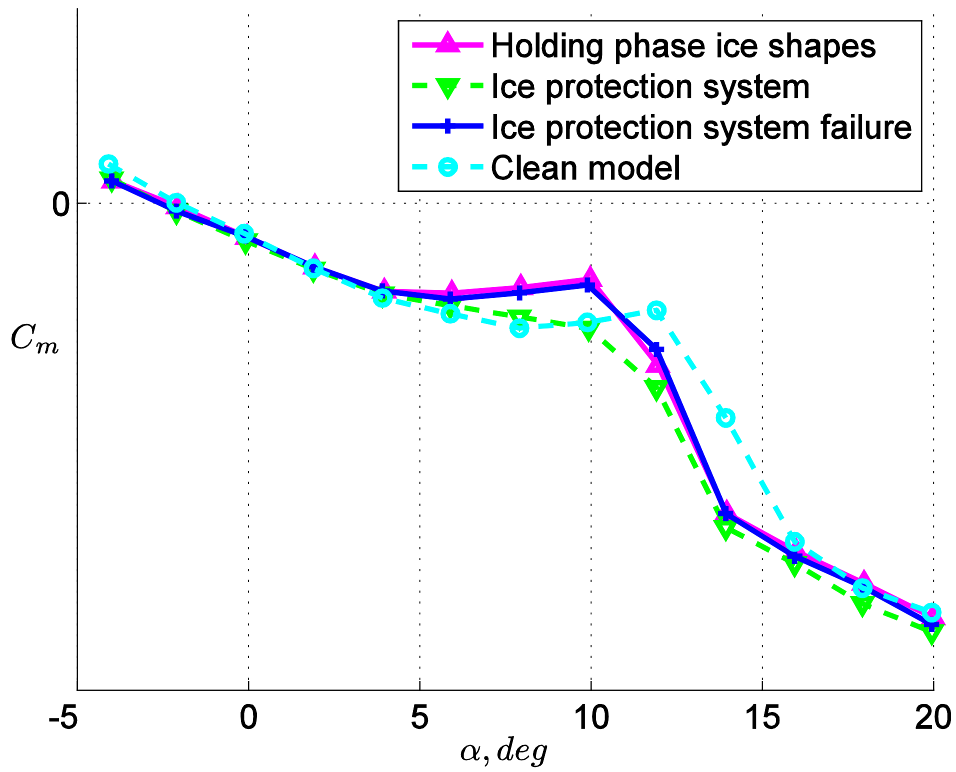

Figure 8. Pitch moment coefficient: ice protection system influence

Working ice protection system decreases of the ice shape sizes and thus delays degradation of the aerodynamic characteristics up to 12 deg. Results obtained in the ice protection system failure conditions are very similar to results for the fully iced model without ice protection system.

4.2 Dynamic tests

The small amplitude forced oscillations are dedicated to determine the unsteady aerodynamic derivatives. The results for the derivatives of the normal force coefficient and pitching moment coefficient are given in Figures 9 and 10.

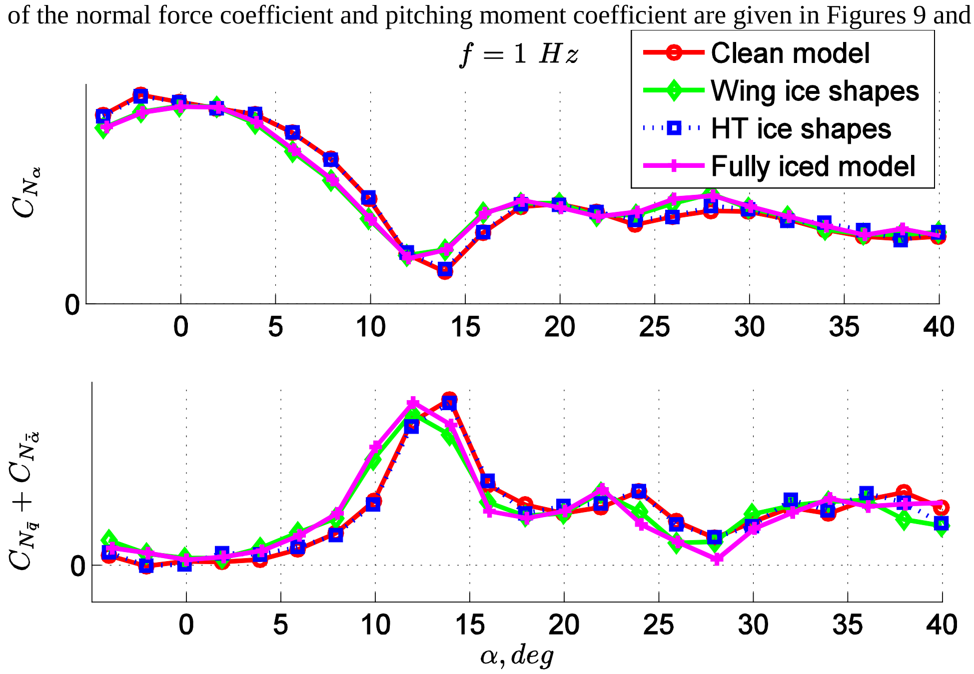

Figure 9. Normal force derivatives

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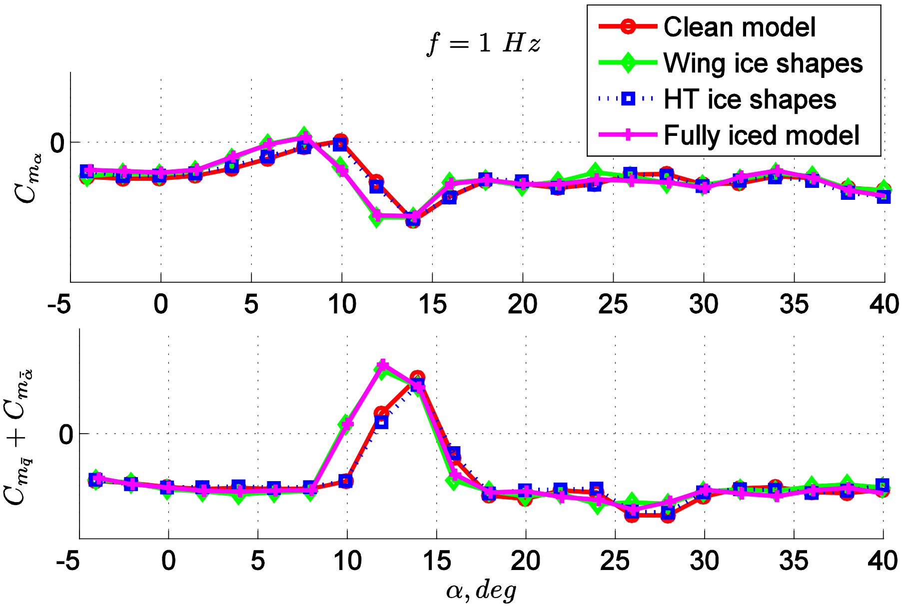

Figure 10. Pitching moment derivatives

One can determine that the aerodynamic derivatives obtained for the clean configuration are similar to results for the configuration with HT-ice, and results obtained for the iced wing are similar to those obtained for the fully iced configuration. This output correlates with the static test results, which stated, that degradation of the aerodynamic characteristics are mostly determined by the wing icing.

The extreme points of static $C_{N_\alpha}(\alpha), C_{m_\alpha}(\alpha)$ and dynamic derivatives $C_{N_{\bar q}}(\alpha)+C_{N_{\dot{\bar\alpha}}}(\alpha)$ and $C_{m_{\bar q}}(\alpha)+C_{m_{\dot{\bar\alpha}}}(\alpha)$ for the iced wing configurations moves to lower angles of attack (α=12 deg) as compared to the clean wing configuration (α=14 deg). One can see that presence of wing icing causes degradation of the aerodynamic characteristics at smaller angles of attack (8 deg instead of 10 deg). Thus, the region of nonlinear variation of aerodynamic derivatives is extended to lower angles of attack due to presence of ice shapes on the wing. Particularly, the pitch damping characteristics has a positive value in the wider region $10 \le \alpha \le 15$ for iced wing configurations as compared to $12 \le \alpha \le 15$ for the clean wing configurations. This fact negatively influences the flight safety since it increases a possibility of self-induced oscillations in case of an aircraft moving into this region. The intensity of the positive damping increases for the iced wing configurations.

Influence of the oscillation frequency on the unsteady aerodynamic characteristics was also studied (see Figure 11). configuration and for the configuration with ice shapes.

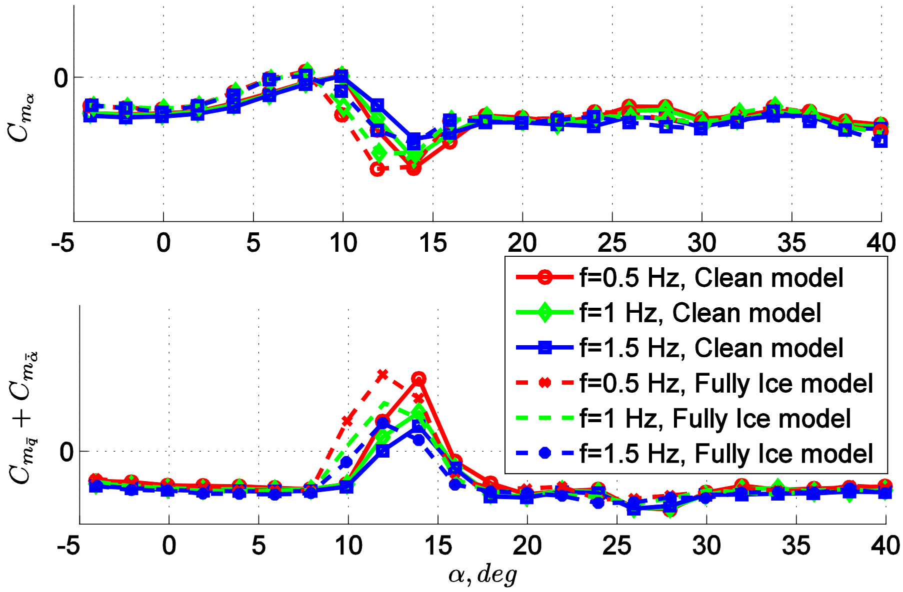

Figure 11. Influence of oscillation frequency on pitching derivatives

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The results, demonstrate the dependency of pitch moment derivatives on the oscillation frequency both for clean. The tendencies are similar, the only difference is that the region on nonlinear variation of damping characteristics is extended to the smaller angles of attack for the configuration with ice shapes.
Influence of the ice protection system on the unsteady aerodynamic coefficients was also evaluated. The results are given in Figures 12 and 13. One can see that ice protection systems do not influence in a considerable way on the derivatives of normal force coefficient. Nevertheless, the ice protection system improves the stability, namely, the static stability derivative C_{m_α} becomes more linear and positive damping region in dynamic derivative $C_{m_{\bar{q}}}(\alpha)+C_{m_{\dot{\bar{\alpha}}}}(\alpha)$ is decreased. In the conditions of the system failure, the aerodynamic derivatives are very similar to the fully iced aircraft characteristics.

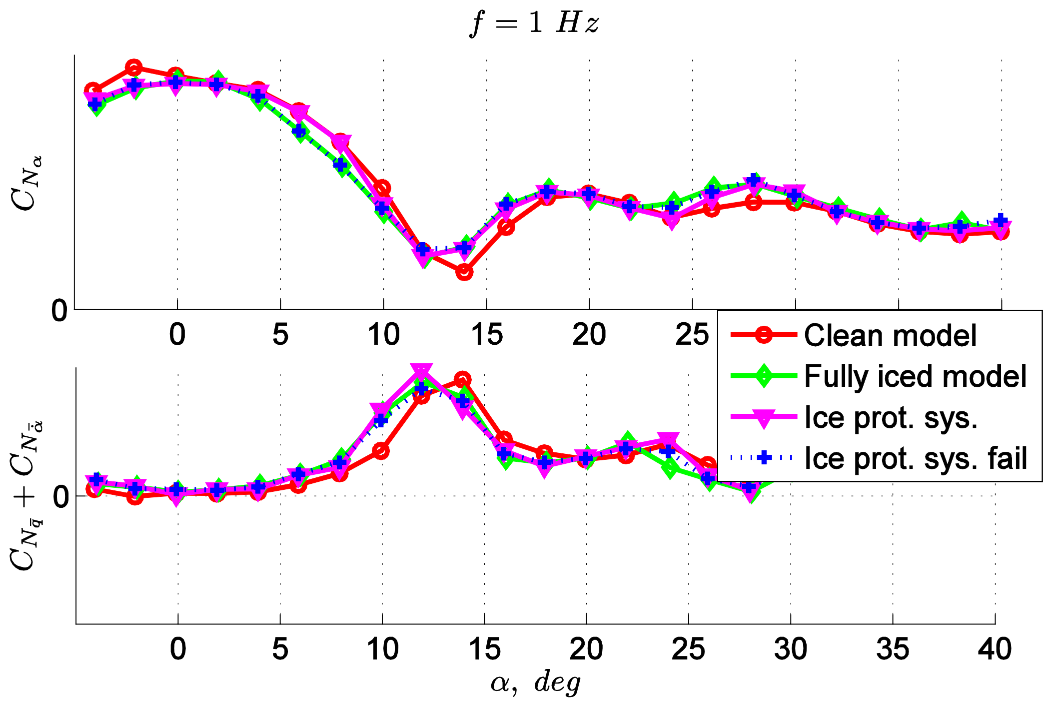

Figure 12. Normal force derivatives: influence of the ice protection system

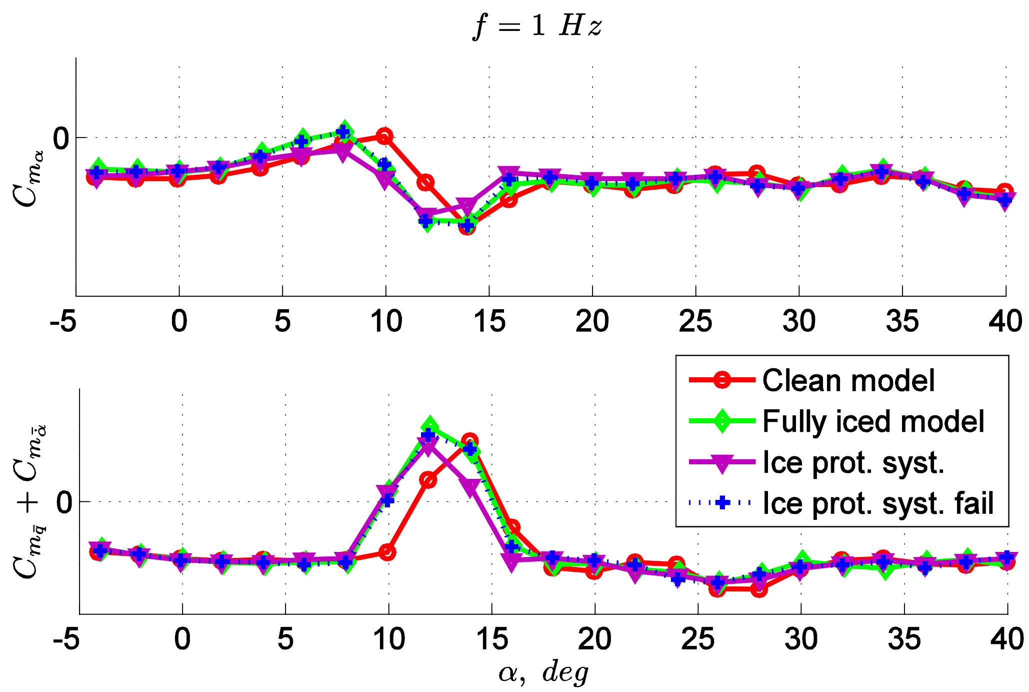

Figure 13. Pitch moment derivatives: influence of the ice protection system

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5. Conclusion

Enabling flight safety in the presence of adverse conditions, such as those caused by environmental factors is a very important problem. This study is a first step in development of aerodynamics model in such conditions for investigations of aircraft dynamics, including pilot simulations.

An experimental research of longitudinal aerodynamic characteristics of the transport aircraft was carried out. The aircraft model was a low-wing monoplane with high aspect ratio wing, a conventional tail unit with a single vertical stabilizer and two wing-mounted engines. Degradation of the aerodynamic characteristics caused by large, glaze-horn icing, corresponding to the holding phase. These ice shapes were selected for consideration because of their relatively large dimensions as compared to the other types of ice accretion scenarious.

The present study was carried out in low-subsonic TsAGI wind tunnel for the aircraft model with relatively small Reynolds number. In addition, the results of flight tests were used in order to validate the wind tunnel data. Comparison of the wind tunnel and flight test results revealed that wind tunnel experiments could predict behaviour of the aerodynamic characteristics of the aircraft with large ice shapes quite well.

Degradation of the aerodynamic characteristics caused by icing, corresponding to the failure of the ice protection system during holding phase was also studied. Contributions to degradation of the aerodynamic characteristics caused by the ice accretion on the wing and on the tail were investigated.

It was found that stall for the iced wing configurations was observed at the angle of attack that was two degrees lower, namely, 10 deg instead of 12 deg. The experimental results showed that the wing icing brought the main contribution to degradation of the longitudinal aerodynamic characteristics. The artificial ice shapes on the HT did not influence significantly.

Large glaze-horn ice shapes corresponding to holding flight phase negatively influenced the longitudinal stability derivatives. Ice shapes caused stall for lower angle of attack and extension of the positive damping region into lower angles of attack, namely $8\deg \le \alpha \le 16\deg$ instead of $10\deg \le \alpha \le 16\deg$. In addition, an increase of positive damping peak was also observed for the iced wing configurations. Ice protection system helped to decrease positive damping peak to the values that were close to the clean wing configurations, remaining the stall angle of attack close to iced wing configurations.

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