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Research on inflight parameter identification and icing location detection of the aircraft

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A B S T R A C T

This paper introduces a research on inflight parameter identification and icing location detection of the aircraft. A quasi-state nonlinear iced aircraft model is constructed. A command input of the aircraft control surfaces is designed in both longitudinal and lateral/directional planes, based on which the Hinf parameter identification algorithm is implemented to provide inflight estimate of the aircraft dynamic parameters. Parameter estimates are adopted as inputs for the icing detection block, which in this paper is built up by using the Probabilistic Neural Network. A database corresponding to different icing locations and icing severities of the aircraft was generated for the training and test of the detection net. Based on the test results, the icing detection work presented in this paper is believed to be applicable for our future studies.

1. Introduction

Aircraft accidents might occur inflight due to the accretion of ice on aircraft, and the primary cause of these accidents is the effect of ice on aircraft stability and controllability [3]. Typically two approaches are used for the aircraft icing problem. Pilots are provided weather information before and during flight to avoid potential icing conditions; or aircraft are thoroughly de-iced before take-off, while an Icing Protection System (IPS) could be operated inflight to remove dangerous ice accretions. For all aircraft, apparently ice avoidance is a more desirable goal; but for most of the commercial flight courses, where revenues and schedules must be maintained, the IPS still occupies an important part in the insurance of safe flight.

Recently, sporadic aircraft accidents indicate that the IPS strategy does not adequately provide safe and reliable flight during icing conditions. The accident of American Eagle ATR-72 crash near Roselawn Indiana killed 68 people in October 1994 [1]. In November 2004, a China Eastern CRJ-200 airplane crashed after take-off in Baotou City, killed 53 people. Both of these two accidents are notable examples of icing accidents occurring on aircraft equipped with the IPS, where either the IPS was not activated timely, or the IPS was activated but not effective. To ensure flight safety of the aircraft, an overall systematic inspection of the icing problem needs to be performed.

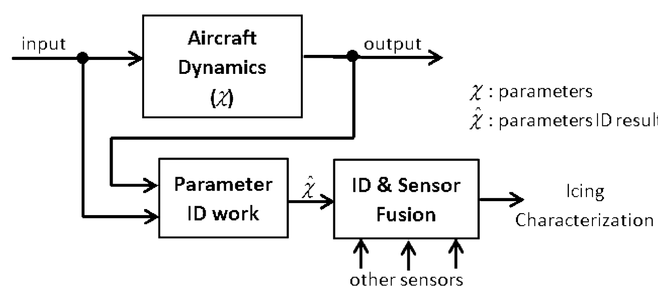

Fig. 1. Icing characterization in IMS.

The Federal Aviation Administration (FAA) and NASA in the United States have sponsored several aircraft icing research efforts [4,5,13]. An Icing Management System (IMS) was proposed by Brag. A brief presentation of the aircraft icing characterizing within IMS is shown in Fig. 1. Fundamental purpose of the IMS is to shift the ice-addressing approach from passively de-ice to actively monitoring and reconfiguring of the aircraft (control), so as to provide reasonable safety margin for the aircraft to operate in a hazardous iced condition. The IMS consists of three basic folds; first, ice must be detected, and the effect of ice on aircraft stability and controllability needs to be evaluated; second, the IPS is operated based on the determined ice effect, and continual real-time update on aircraft icing severity is provided for the pilots; third, flight control laws of the aircraft might be adjusted, if severe ice is determined to induce a potentially unstable/uncontrollable flight condition.

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Table 1
Dynamic parameters of the Twin Otter in clean and iced configurations.

	C_{Z0}	$C_{Z\alpha}$	C_{Zq}	$C_{Z\delta e}$	$\bar{C}_{x0}$	K	C_{m0}	$C_{m\alpha}$	C_{mq}	$C_{m\delta e}$
Clean	−0.380	−5.660	−19.970	−0.608	−0.041	0.052	0.008	−1.310	−34.200	−1.740
Wing	−0.380	−5.342	−19.700	−0.594	−0.050	0.053	0.008	−1.285	−33.000	−1.709
Tail	−0.380	−5.520	−19.700	−0.565	−0.046	0.053	0.008	−1.263	−33.000	−1.593
Both	−0.380	−5.094	−19.700	−0.550	−0.062	0.057	0.008	−1.180	−33.000	−1.566

	$C_{Y\beta}$	C_{Yp}	C_{Yr}	$C_{Y\delta r}$	$C_{l\beta}$	C_{lp}	C_{lr}	$C_{l\delta a}$	$C_{l\delta r}$	$C_{n\beta}$	C_{np}	C_{nr}	$C_{n\delta a}$	$C_{n\delta r}$
Clean	−0.6	−0.2	0.4	0.15	−0.08	−0.5	0.06	−0.15	0.015	0.1	−0.06	−0.18	−0.12	−0.001
Both	−0.48	−0.2	0.4	0.135	−0.072	−0.45	0.06	−0.135	0.0138	0.08	−0.06	−0.169	−0.11	−0.001

The aircraft icing research in Fudan University basically follows the formulation of the IMS framework. Specifically, our system depends upon inflight icing characterization of the aircraft. Parameter identification technique is implemented to provide inline estimates of the aircraft dynamic parameter, after which icing characterization information (location and severity) could be obtained. Based on the characterization knowledge, cockpit display is designed for pilot notifications, and feedback control laws of the aircraft might be reconfigured to guarantee a safe flight in the iced condition.

One difference in our work compared with the IMS lies in the superiority distribution between human pilots and the control system. Specifically, in the IMS work, control system was believed to be more useful (superior) for the aircraft icing problem, as when the icing severity is determined to be potentially dangerous, control system will be used to limit/substitute human control of the aircraft. In our work, however, control system is treated as an assisting tool for human pilot, and generally it will not substitute human control of the aircraft, although certain protection laws is acceptable under human monitoring. Another difference of our research lies in a more practical context: in the IMS work, parameter identification and aircraft icing characterization was developed based on the longitudinal linearized model, while in our work, a quasi-state nonlinear 6 degree-of-freedom aircraft model is adopted. Certainly this model would add some complexity, but it is believed that this model could represent more accurately the real behavior of the aircraft, and could provide a more solid basis for the aircraft icing research work.

In this paper we mainly discuss the parameter identification framework and the detection work of icing characterization in Fudan University. Note that in the IMS, parameter ID technique is formulated to be fused with sensors data for the aircraft icing characterization. While the sensors could provide real-time information of the aircraft icing, the parameters ID work would get to the core of aircraft icing problem—stability and controllability parameters change. A quantitative knowing of the aircraft icing could be obtained based on the ID results, which is most crucial to the construction of further icing protection controls. Generally, the parameter ID-based detection could provide more detailed information of the aircraft icing, and is believed to be great complimentary to the traditional sensor-based detection methodology. Currently in our work, the icing characterization adopts the parameter ID results only, similar to the work introduced in Ref. [14]. While the onboard sensors will be incorporated within the system in the future, the work presented herein may provide a conservative stance for our current research.

Specifically, this paper is constructed as follows. Iced aircraft dynamic model is presented in Section 2. Effect of ice on the aircraft is modeled as a linear relation; in conjunction with aircraft motion equations, simulation of the aircraft with different icing locations and different icing severity levels could be conducted. In Section 3, a robust Hinf parameter identification algorithm is introduced. This ID method is expected to tolerate nonlinearities within aircraft motion equations, and was implemented to identify aircraft dynamic parameters under disturbances/measurement noise perturbation. Detailed framework of the Hinf ID process is introduced in Section 4. In the IMS work, only longitudinal work was discussed, while in this paper lateral/directional results are also included. Response of the aircraft was specifically presented in this section to assess potential effect of the ID maneuver on aircraft safety and passenger-ride quality. In Section 5, the icing detection work is constructed by using the Probabilistic Neural Network (PNN). This work is expected to detect different icing locations, which in this paper includes clean, wing iced, tail iced, and wing–tail both iced scenarios. Training procedure and test result of the network were discussed in this section. Finally, Section 6 contains a general conclusion of this paper, and some issues that warrant close interest in future studies.

2. Aircraft dynamic model

2.1. Ice effect on parameters

In Ref. [5], Brag proposed a representative model of the effect of ice accretion on aircraft dynamics:

$$C_{(*)iced} = C_{(*)clean}(1 + \eta_{ice} k_{C*}) \tag{1}$$

where η_{ice} is an icing severity parameter, k_{C*} is the coefficient icing weight which depends on the parameter being modified; $C_{(*)clean}$ is the clean (not iced) aircraft parameter, and $C_{(*)iced}$ indicates the iced parameter. In our work, dynamic model of the aircraft is established based on the NASA Twin Otter aircraft icing research plane. Both clean and iced parameters of this aircraft are detailed in Table 1 [5]. The iced parameters in the table are representative of icing severity $\eta_{ice} = 0.2$; k_{C*} could then be calculated as the associated slope from particular parameters under different icing locations. By assigning different values to η_{ice}, cases with different levels of icing severity could be simulated. In this paper, η_{ice} is chosen as $\{0, 0.2, 0.4, 0.6, 0.8, 1\}$, wherein $\eta_{ice} = 0$ indicates the clean aircraft, and $\eta_{ice} = 1$ is the highest level of different icing cases.

2.2. Nonlinear dynamic model

Motion equations adopted in this paper borrow directly from the 6 degree-of-freedom nonlinear aircraft dynamics [7]. For all cases, the work in this paper is simulated with an initial condition of steady level flight at altitude 1713 m, and velocity 57.3 m/s. Trimmed results are consistent with the results mentioned in Ref. [5]. Generally when the icing severity increases, the aircraft pitches up to a larger angle of attack, and elevator is deflected upward more to counteract the pitch torque; also thrust needs to be added to compensate for the increase of drag.

2.3. Disturbances and measurement noise

Performance of the iced aircraft under different disturbances and measurement noise was discussed in Ref. [5]. A further research work of the micro-bust and gravity wave effects on the