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Differentiation between Appendix O and Appendix C Icing Conditions in Flight Using the Collins Ice Differentiator System

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Abstract

Protecting against atmospheric icing conditions is critical for the safety of aircraft during flight. Sensors and probes are often used to indicate the presence of icing conditions, enabling the aircraft to engage their ice protection systems and exit the icing cloud. Supercooled large drop icing conditions, which are defined in Appendix O of 14 CFR Part 25, pose additional aircraft certification challenges and requirements as compared to conventional icing conditions, which are defined in Appendix C of 14 CFR Part 25. For this reason, developing sensors that can not only indicate the presence of ice, but can also differentiate between Appendix O and Appendix C icing conditions, is of particular interest to the aviation industry and to federal agencies. Developing detectors capable of meeting this challenge is the focus of SENS4ICE, a European Union sponsored project. While participating in the SENS4ICE Project, Collins Aerospace has developed an ice detection and differentiation sensor known as the Collins Ice Differentiator System (Collins-IDS). A flight test campaign evaluating the performance of the Collins-IDS in natural icing conditions was completed; the results of which are the focus of this technical paper. During the campaign, the Collins-IDS successfully detected the presence of ice and determined, with high accuracy whether that ice was Appendix C or Appendix O. Additional testing in Appendix O icing conditions, either in an icing wind tunnel or during a flight test in natural icing conditions, will benefit the future development of the Collins-IDS.

Introduction

The SENS4ICE project is an EU-funded consortium made up of 17 international partners focused on developing sensors capable of detecting and differentiating between App C and App O icing conditions [1, 2, 3, 4]. Although developing sensors capable of differentiating within App O (i.e., freezing drizzle and freezing rain) is also of interest, this falls outside the SENS4ICE project's scope [5]. In addition, App O freezing rain conditions were not explicitly sought out or identified during testing, so discrimination performance within App O cannot be properly evaluated at this time. To facilitate the development and validation of these new sensor technologies, three icing wind tunnels (IWT) and two flight test platforms have been made available to the consortium. In the early stages of the SENS4ICE project, each sensor developer had the opportunity to test their technology in one or more of the IWTs [1, 2, 3, 4].

Collins Aerospace is a global provider of aerospace systems, including ice protection systems (IPS), and is participating in the SENS4ICE project in two capacities: As a sensor developer and an IWT provider. The novel ice detector that Collins designed to meet this challenge is known as the Collins Ice Differentiator System (Collins-IDS) [1].

The project ended in April 2023, culminating in two natural icing flight test campaigns in which sensor developers had the opportunity to participate [6]. The European Flight Campaign took place in April 2023 and utilized an ATR 42-320 operated by SAFIRE; a French airborne research facility based in Toulouse France [6, 7]. The North American Flight Campaign took place from late-February to early-March 2023, and utilized an Embraer Phenom 300 (P300) operated by the aircraft's manufacturer Embraer S.A. [6, 8]. Collins elected to participate in the North American Flight Campaign due to the favorable USA-based location and their familiarity with the P300 aircraft from past flight test programs.

A previous technical paper on the Collins-IDS was published and presented by the authors in June 2023 at the SAE International Conference on Icing of Aircraft, Engines, and Structures in Vienna, Austria [1]. That paper focused on the work leading up to the flight test campaign, including IWT and on-aircraft integration testing. Over the subsequent months, refined flight test data, which was received just two weeks before the SAE International

Conference on Icing, was fully analyzed. Following some minor modifications to the detection algorithm, the Collins-IDS is capable of detecting and differentiating between Appendix C and Appendix O icing conditions on the P300 aircraft. While some summary information about the IWT and integration testing will be included herein for reference, the results of the Natural Icing Flight Test will be the focus of this paper.

Collins Ice Differentiator System

The Collins-IDS technology is based on measuring heat flux variations in different icing conditions using a metallic heater [1]. The system builds upon a patent pending ice detection technology based on thermal response to a heat impulse that changes from dry to icing conditions. The Collins-IDS is shown schematically in Figure 1.

The Collins-IDS is made of three components (see Figure 2 for an image of each) [1]:

1. Sensing Element (SE) that uses a proven and certified construction made of high temperature composite, temperature sensors and a metallic heater that measures heat flux distribution and communicates this to the rest of the system.
2. A Power Interface Unit (PIU) that provides the necessary power to the sensing element.
3. Control Unit (CU) that analyses the measurements and makes recommendations on icing conditions (i.e., Dry Air, App C or App O). Detection and differentiation is performed by a built-in algorithm within the CU.

For the flight test, a National Instruments (NI) CompactRIO™ was used instead of a bespoke controller primarily due to cost considerations [9]. The CompactRIO™ was selected due the maturity of the product and the configuration flexibility it offers. Additionally, the CompactRIO™ uses LabVIEW™ as its programming language, making it easy to modify the detection algorithm and the underlying control code as needed during testing [9].

The SE was initially designed to mount to the P300's horizontal stabilizer but was later redesigned to mount to the vertical stabilizer. The leading-edge surface of the horizontal stabilizer is ordinarily protected by a bleed air IPS and, to accommodate the Collins-IDS SE, that system would have required modification. Unlike the horizontal stabilizer, the vertical stabilizer is ordinarily an unprotected surface, so the SE could be mounted to it without making any significant modifications to the aircraft [1]. For that reason, the inside surface of the vertical stabilizer leading-edge was selected as the mounting position for the SE. The SE could have alternatively been bonded to the outside surface of the leading-edge, but this was avoided to make wire ingress simpler and to ensure that the aerodynamic properties of the vertical stabilizer were not disrupted. The decision to switch from the horizontal stabilizer to the vertical stabilizer was made mid-project and, because the geometries of the horizontal and vertical stabilizer are significantly different, triggered a redesign of the SE.

In general, the installation of the Collins-IDS on aircraft is flexible and the SE can theoretically be installed anywhere on the aircraft that is sensitive to inflight icing. Some examples include: the vertical/horizontal stabilizer, wings/wing tips, tail, nose, or engine inlet as appropriate for different types of aircraft (i.e., rotorcraft or fixed-wing). Where bonding the SE to the inside surface of the leading-edge is impossible (for example, on surfaces where there is no internal cavity), the SE can instead be mounted externally.

Finally, the system is scalable to include one or multiple sensing elements positioned on sensitive areas of the airplane. The sensing elements can be powered individually but controlled by a master controller. Consequently, the Collins-IDS can form the backbone of a "smart-IPS", leading to the reduction of electrical power consumption by an aircraft's IPS.

FIGURE 1 Collins-IDS System Schematic [1]

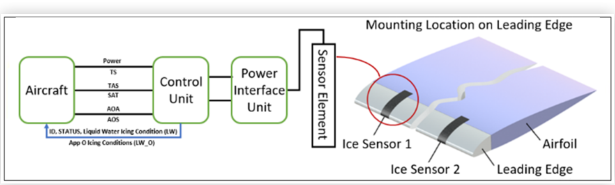
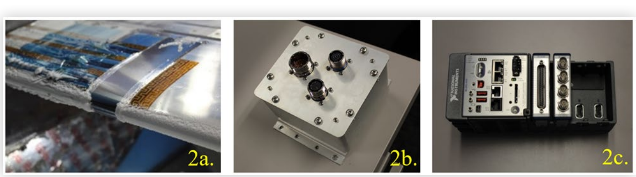


FIGURE 2 Collins-IDS System Components, (2a.) Sensing Element, (2b.) Power Interface Unit, (2c.) Control Unit



IWT and Aircraft Integration Testing

The Collins-IDS was tested during six IWT test campaigns which are detailed in Table 1. These IWT tests were used to develop and refine the ice detection and App C/App O differentiation algorithm and to integrate the three constituent components of the Collins-IDS. The first-generation SE was tested in the IWT using a truncated model designed to replicate the Embraer P300's horizontal stabilizer and was used for the first four IWT test campaigns. The second-generation SE was tested in the IWT using a truncated model designed to replicate the Embraer P300's vertical stabilizer and was used in the remaining two IWT test campaigns. For each IWT test,

TABLE 1 Icing Wind Tunnel Testing Summary [1]

IWT Test	Test Type	Duration	Description
Round 1, May 2020	Developmental	40 Hours	Feasibility tests to validate CFD models over Dry, App C and App O conditions and to verify App C/O discrimination.
Round 2, Oct. 2020	Developmental	40 Hours	Tested operation of integrated system over a wide range of icing conditions. Data used to validate the detection algorithm and its ability to detect and discriminate App C/O conditions.
Round 3, Jan. 2021	Developmental	40 Hours	Demonstrated (1) reduction in power requirements and improved sensor performance, and (2) ice detection and differentiation between App C and App O icing conditions continuing the sensor's progress toward flight testing.
Round 4, Mar. 2021	Developmental	20 Hours	Tested at additional conditions within the App O icing envelope. The data was used to expand the detection range and to demonstrate the efficacy of the sensor in differentiating between App C and App O, as well as to extend the number of points available for simulation verification.
Round 5, Apr. 2022	Developmental	40 Hours	Evaluated the performance of the second-generation sensor, which was redesigned to be mounted on the vertical stabilizer. Data used to revalidate the detection algorithm and its ability to detect and discriminate App C/O conditions given the design changes to the detector.
Round 6, Sept. 2022	Integration	40 Hours	Previous rounds of IWT testing used a LabVIEW™ program to control the Collins-IDS SE instead of the PIU and CU which did not participate in the testing. The purpose of this round of IWT testing was to integrate the three components of the Collins-IDS to ensure that the PIU and CU could effectively control the SE while on aircraft and to refine the detection algorithm accordingly. Overtemperature and WoW safety protocols for the CU were also tested.

the model was mounted horizontally with the SE positioned at the centerline of the test section.

Following the completion of the icing wind tunnel testing, further integration testing was performed on-aircraft at Embraer's GPX Facility in Gavião Peixoto, Sao Paulo, Brazil. This integration testing included [1]:

- WoW and OAT safety protocol testing, this time with the flight test computer sending signals to the CU.
- Tested the Collins-IDS ability to stabilize the SE's internal temperature at the desired value.
- Tested the communications between the Collins-IDS CU and the Phenom 300's flight test computer.
- EMI testing was performed.

Following only minor changes to the control software, the on-ground, on-aircraft integration tests were completed successfully, and the Collins-IDS was approved for flight testing [1].

Natural Icing Flight Test Campaign

The SENS4ICE project culminated in a natural icing flight test campaign which the Collins-IDS and several other sensor developers participated in [1]. The base of operations for the flight test campaign was the St. Louis Regional Airport in East Alton, IL. The first flight test began on February 22, 2023, and the final flight test finished on March 10, 2023. The campaign was 25FH long spread over 15 individual flights [10]. The Collins-IDS operated during the 12 flights that were conducive for App O icing. These 12 flights are summarized in Table 2 [1]. The corresponding flight maps are also shown visually on page 6 of reference 10 [10]. The flights were concentrated primarily in the Great Lakes region of the USA; however, some took place elsewhere in the American Midwest. In the previous paper published on the Collins-IDS, a similar table was included and listed 13 flights, instead of 12. However, after publication, it was realized that one of those flights was included erroneously.

During the flights, the aircraft encountered 55 distinct icing events [10]. To characterize these encounters, the Embraer P300 was equipped with two key instruments used for reference measurements.

The first instrument was the Cloud Combination Probe (CCP) which was used to characterize the droplet size distribution and MVD of the icing clouds [11, 12]. The CCP probe is manufactured by Droplet Measurement Technologies (DMT), and the probe used in the flight test is owned and operated by Embraer. The other probe was an Ice Crystal Detector (ICD) which was used to determine the LWC of the icing clouds [13]. The ICD is manufactured by Science Engineering Associates (SEA) and the probe used in the flight test was owned by the manufacturer.

The data recorded by these two instruments was analyzed by the German Aerospace Center (DLR) and SEA to determine if ice was encountered, when that icing encounter began and what type of ice was encountered (i.e., Appendix C or Appendix O). This established the "ground-truth" by which to evaluate the ice detection/differentiation performance of the Collins-IDS, and the performance of the other probes participating in the SENS4ICE project. There was some subjectivity involved in the determination of whether an icing condition was Appendix C or Appendix O which should be kept in mind when reviewing the flight test results presented herein.

TABLE 2 Natural Icing Flight Test Summary [1]

Flight No.	Date DD/MM/YY	Departure Airport	Arrival Airport	Flight Duration
1	22/02/23	St Louis Regional	St Louis Regional	0:39
2	23/02/23	St Louis Regional	Chicago O'Hare International	2:45
3	23/02/23	Chicago O'Hare International	St Louis Regional	1:12
4	25/02/23	St Louis Regional	Eugene F Kranz Toledo Express	2:03
5	25/02/23	Eugene F Kranz Toledo Express	St Louis Regional	1:37
6	01/03/23	St Louis Regional	Des Moines International	2:45
7	01/03/23	Des Moines International	St Louis Regional	2:12
8	06/03/23	St Louis Regional	South Bend International	1:07
9	08/03/23	St Louis Regional	Quad Cities International	2:21
10	09/03/23	St Louis Regional	St Louis Regional	1:23
11	10/03/23	St Louis Regional	Terre Haute International	2:15
12	10/03/23	Terre Haute International	St Louis Regional	1:08

FIGURE 3 Vertical Stabilizer Leading Edge Section - Embraer Phenom 300

In addition, when interpreting the results described in the Flight Test Results section of this technical paper, it is important to note that the reference measurement instrumentation (i.e. the CCP and ICD) are subject to measurement errors, although the magnitude of the error has not been communicated by the SENS4ICE consortium at this time.

Page 6 of reference 10 contains an image of the actual Embraer P300 aircraft used in the flight test. The CCP and ICD reference probes can be seen mounted to the top of the aircraft's fuselage near the windshield [10]. The section of vertical stabilizer where the Collins-IDS SE is internally mounted can also be seen in the image. For reference, the leading-edge from this section of vertical stabilizer is shown in Figure 3. The approximate location where the Collins-IDS SE is internally bonded to the vertical stabilizer is outlined by the red dotted area.

Flight Test Results

Several plots showing examples of the Collins-IDS output are included in Figure 4, Figure 5, and Figure 6 [14]. In each of these figures, the green colored area indicates that the aircraft is operating in dry air conditions, the blue colored area indicates that the aircraft is operating in Appendix C icing conditions, and the red area indicates that the aircraft is operating in Appendix O icing conditions. Each figure contains a pair of plots: The top plot is the Collins-IDS output, and the lower plot is the output from the flight test computer. The upper and lower plots

FIGURE 4 Collins-IDS Output, Flight Test Result Example #1 [14]

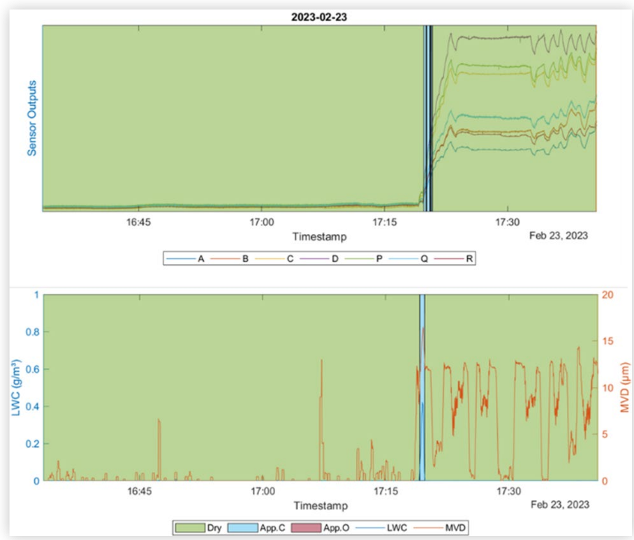


FIGURE 5 Collins-IDS Output, Flight Test Result Example #2 [14]

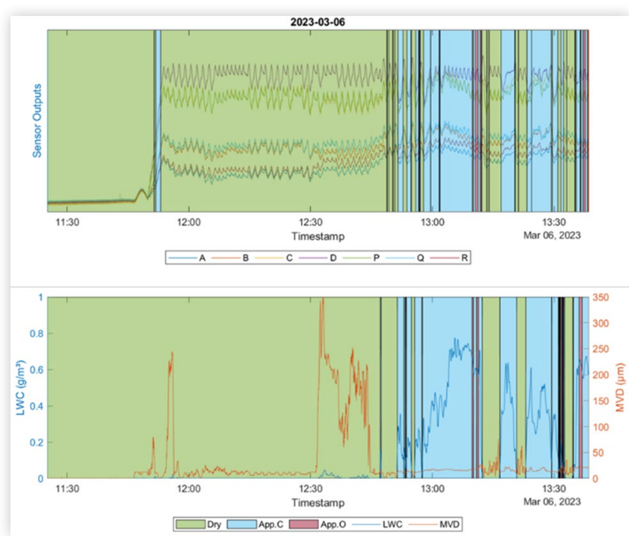
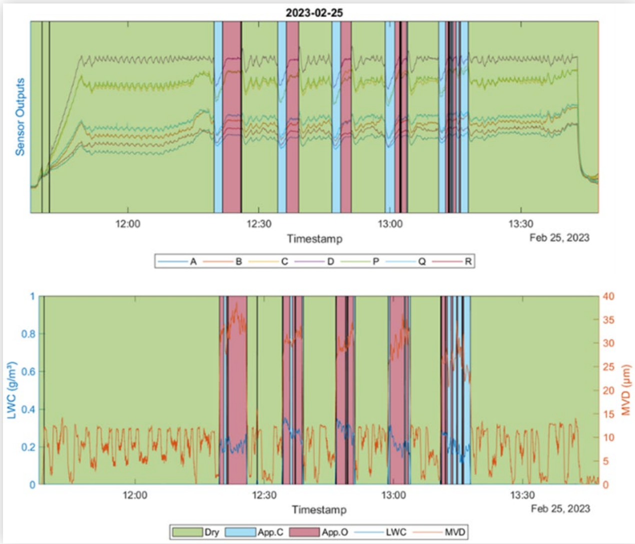


FIGURE 6 Collins-IDS Output, Flight Test Result Example #3 [14]



are shown in pairs so that the output of the Collins-IDS can be directly compared to the output of the flight computer by observing how well the colored areas align along the x-axes.

Figure 4 shows the output of the Collins-IDS following a single Appendix C icing encounter. As evidenced by how well the colored areas in the figure match up, the Collins-IDS indicated Appendix C icing at approximately the same time as the reference measurements [14].

Figure 5 shows the output of the Collins-IDS following a series of Appendix C icing encounters [14]. There are a several Appendix C icing encounters in rapid succession shown at the right-hand side of the plots. Here the colored areas match up very well which suggests that the Collins-IDS managed to detect Appendix C icing at approximately the same time as the reference measurements. On the left-hand side of the plot, the Collins-IDS indicated Appendix C icing while the flight computer did not (i.e., the flight computer indicated dry air conditions). This point in time corresponded with a spike in MVD, however, it was determined by the SENS4ICE consortium that this did not constitute an icing encounter. This misclassification may have been the result of error in one, or both, of the reference instruments. Alternatively, the misclassification may be the result of the Collins-IDS still being in its startup phase when the alleged encounter occurred [14].

Figure 6 shows the output of the Collins-IDS following a series of Appendix O icing encounters [14]. In each case, the Collins-IDS managed to detect the presence of Appendix O icing, however, the Collins-IDS indicated Appendix C icing for a brief period of time before correctly classifying the encounter.

The complete results are summarized in the confusion matrix shown in Table 3 [14]. When the plane was operating in dry air, the Collins-IDS correctly classified the condition 97.17% of the time. When operating in Appendix C icing, the Collins-IDS correctly classified the condition 91.53% of the time but detected some form of icing (i.e., Appendix C or Appendix O) 98.31% of the time. Finally, when operating in Appendix O icing, the Collins IDS correctly classified the condition 79.27% of the time but detected some form of icing 97.56% of the time.

TABLE 3 Confusion Matrix - Flight Test Results [14]

		Predicted Class		
		Dry	**App.C**	**App.O**
True Class	**Dry**	97.17%	2.83%	0%
	App.C	1.69%	91.53%	6.78%
	App.O	2.44%	18.29%	79.27%

Total loss can be used to quantify the overall performance of the Collins-IDS algorithm [15]. Total loss gives, as a percentage, the number of icing encounters that were misclassified out of the entire population [15]. For example, a total loss of 0% would indicate an algorithm that misclassified none of the icing events that it encountered, while a total loss of 50% would indicate an algorithm that misclassified half of the icing events that it encountered. For the purposes of evaluating the performance of the Collins-IDS, total loss is calculated via the following equation:

$$Total\ Loss = \frac{False\ Positives + False\ Negatives}{Total\ Number\ of\ Events} \times 100\%$$

The detection algorithm was trained on the flight test data to minimize the total loss value, in turn maximizing the algorithm's overall accuracy. For the Natural Icing Flight Test, the Collins-IDS ultimately achieved a total loss of 6.26%.

Conclusions

The Collins Ice Differentiator System successfully completed 25 total hours of flight testing. 4.4 hours of that time were spent in icing conditions, of which 37min were in Appendix O icing. After a complete analysis of the results was performed, the Collins-IDS demonstrated its capabilities as an effective ice detector, distinguished icing conditions from dry and differentiating between Appendix C and Appendix O ice conditions with high accuracy during flight.

When an Appendix C icing condition was encountered, the Collins-IDS correctly classified it 91.53% of the time. Of the Appendix C icing encounters that were misclassified, 1.69% were underclassified as dry. When an Appendix O condition was encountered, the Collins-IDS correctly classified the condition 79.27% of the time and underclassified the condition as dry 2.44% of the time and as Appendix C icing 18.29% of the time.

Given that Appendix O conditions might be more detrimental to aerodynamic performance than Appendix C conditions for certain applications, it is important that underclassification is avoided. While overclassifying should be minimized as well, it is preferred over underclassification because it will result in a pilot taking precautionary measures against in-flight icing. For the purposes of this discussion, underclassification refers to misclassifying Appendix C icing as dry air and/or misclassifying Appendix O icing as either Appendix C icing or dry air. By contrast, overclassification refers to misclassifying Appendix C icing as Appendix O and/or misclassifying dry air as Appendix C or Appendix O icing.

As previously stated, the algorithm was trained to maximize overall accuracy, ultimately achieving a total loss of 6.26%. Due to the nature of the data model used in the detection algorithm, it can be retrained to favor an increase in overclassifications in exchange for a reduction in underclassifications, producing an algorithm that is conservative, which is beneficial for aircraft safety.

Future Work

As previously stated, the Collins-IDS CU used in the flight test was a NI CompactRIO™. The CompactRIO™ performed excellently for the purposes of the flight test; however, the use of an off-the-shelf controller will not be acceptable for a production version of the Collins-IDS. For that reason, there are plans to design and produce a dedicated CU for use in the Collins-IDS. The PIU and CU could also be integrated into a single LRU which would produce a heavier and more complicated unit but would simplify the overall system architecture. One or both options may be pursued by Collins to meet the needs of the market.

The Collins-IDS would also benefit from additional icing wind tunnel and natural icing flight testing. This would provide an opportunity to acquire more data to refine the algorithm and improve the detection/differentiation performance of the Collins-IDS. The testing would also provide an opportunity to test the Collins-IDS for different aircraft applications, such as bonding the SE to an engine inlet or wing. Minor adjustments to the detection algorithm may be required for different aircraft applications.

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Definitions/Abbreviations

App. C - Appendix C to 14 CFR Part 25

AOA - angle of attack

AOS - angle of sideslip

App. O - Appendix O to 14 CFR Part 25

CCP - Droplet Measurement Technologies Cloud Combination Probe

CFR - Code of Federal Regulations

CFD - computational fluid dynamics

Collins-IDS - Collins Ice Differentiator System

CU - Collins Ice Differentiator System Control Unit

DLR - German Aerospace Center

DMT - Droplet Measurement Technologies

EMI - electromagnetic interference

FH - flight hours

ICD - Science Engineering Associates Ice Crystal Detector

IPS - ice protection system

IWT - icing wind tunnel

LRU - line-replaceable unit

LWC - liquid water content

MVD - median volume diameter

NI - National Instruments

OAT - outside air temperature

PIU - Collins Ice Differentiator System Power Interface Unit

SE - Collins Ice Differentiator System Sensor Element

SEA - Science Engineering Associates

SAT - static air temperature

SLD - supercooled large drop icing conditions

TAS - true airspeed

TS - time stamp

WoW - weight on wheels

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