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FLYING WITH ICE - AN OVERVIEW OF DLR RESEARCH IN FLIGHT MECHANICS WITH ICING INFLUENCE DURING THE LAST DECADE

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Summary of Presentation

A very brief overview is given on the icing research done at DLR's Institute of Flight Systems between 2011 and 2021. The highlights of the research results are shown and references to supplemental publications with more specific results are provided.

Keywords
flight mechanics; supercooled large droplet icing; flight test

1. MOTIVATION FOR ICING RESEARCH

Icing can have hazardous effects on airplane performance characteristics. It can also be a limiting factor for the safe flight envelope. Icing-induced change of the aircraft's dynamic behavior and potential premature stall raise the need for pilot situational awareness and an adaptation of any aircraft control strategy. During the last decades, various accidents worldwide have shown the severity of icing related degradations as well as pilots' difficulties to cope with changes in aircraft behavior [1–3]. One major cause for these accidents was that with rising air traffic aircraft were increasingly operated in certain icing conditions containing supercooled large water droplets (SLD) against which current aircraft were not protected. The certification of (modern) transport aircraft for flight into icing conditions was mainly based on the certification requirements given in the so-called App. C to e.g. CS-25. But with the identified hazard to fixed-wing aircraft resulting from the supercooled large droplets the aviation agencies issued the new App. O to the existing certification requirements. From now on, manufacturers of newly developed transport airplanes must prove that the airplane is also safe for flight into even more hazardous atmospheric icing conditions.

The new certification requirements led to a demand for acceptable means of compliance and consequently the question about a way to safely demonstrate the remaining aircraft capabilities in flight for the case of SLD icing. These icing conditions can pose a high risk to the aircraft and crew, which results in a large effort to assure aircraft safety during flight test. Hence, it is mandatory to analyze the possible aircraft performance and control degradation introduced by SLD icing and also monitor the aircraft's remaining capabilities during the complete test flight. The distinct impact of SLD ice on the overall aircraft characteristics is not easy to predict and still an aspect of current aviation research.

2. SULADI PROJECT

As the overall need for a better understanding of the SLD-icing effects on aircraft was identified as a research gap, a German nationally funded research project named SuLaDI (Supercooled Large Droplet Icing) was established between DLR and TU Braunschweig (2011-2016). Several aspects of icing – from built-up to de-icing – were addressed with this project. The results of the fundamental research done in this project were merged in a simulation of the former DLR research aircraft VFW 614 “ATTAS” (see FIG. 1) and finally brought to the full motion simulator AVES for essential investigations of flight in icing conditions. The major achievements in modeling of leading-edge icing effects on aircraft dynamics during the SuLaDI project are given e.g. in Refs. [4–6]. FIG 2 shows an example of these SLD-caused leading-edge ice shapes (on wing tip) used for the analysis in the project. These shapes were calculated for 10 minute

FIG 1. DLR research aircraft VFW 614 “ATTAS” used as base for analysis in SuLaDI

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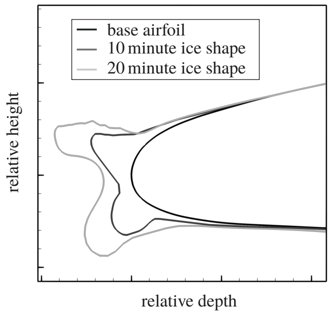

FIG 2. **Wing tip ice shapes used for ATTAS flight mechanics analysis in the SuLaDI project [4]**

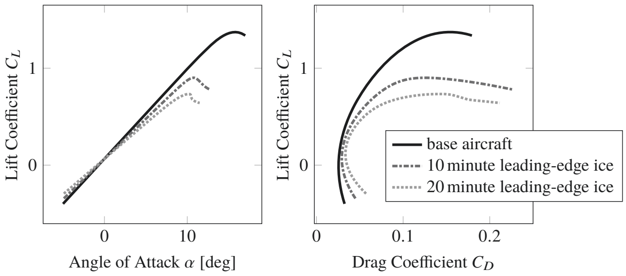

FIG 3. **Change of ATTAS aerodynamics with different leading-edge ice configurations: lift curve and drag polar plots [4]**

and 20 minute icing encounters. The corresponding degradation on aerodynamics is given in FIG. 3.
The corresponding degradation of ATTAS flight performance is given by e.g. the change of the required thrust-to-weight ratio TWR (see FIG. 4) which is significantly shifted towards the limit of $\mathrm{TWR}_{\max}$. A further analysis and detailed evaluation of the flight dynamics' changes are given in Ref. [6].

3. DLR-EMBRAER RESEARCH COOPERATION

In parallel to the SuLaDI-project, a joint research activity between DLR and Embraer was conducted between 2012 and 2016 to further investigate the icing degradation of aircraft in general but with a specific view to SLD conditions. The major advantage of this research cooperation was the focus on flight test and flight data analysis with respect to different icing cases (App. C and App. O), which is highly important to answer some questions about the specific effects of icing on aircraft characteristics. For this cooperation, Embraer provided a Phenom 300 prototype (see FIG. 5) as flight test bench and several flight tests had been conducted with a joint DLR-Embraer flight test crew.

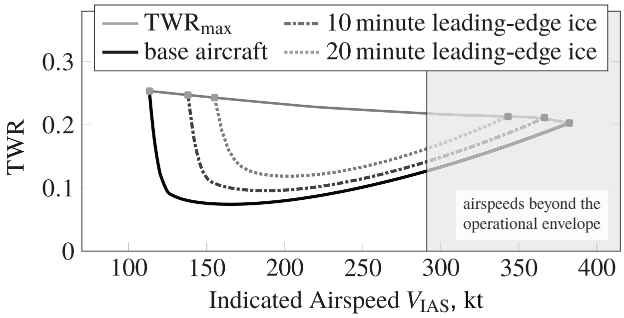

FIG 4. **Example of ATTAS flight performance evaluation with different ice shapes: indicated airspeed V_{IAS} vs. thrust-to-weight ratio TWR; from [6]**

FIG 5. **Embraer Phenom 300 prototype aircraft used during different flight test within the research cooperation**

FIG 6. **Schematic illustration of different artificial wing ice shapes; left: run-back ice, mid: leading-edge ice, right: SLD-ice configuration**

The aircraft was equipped with artificial ice shapes (see FIG. 6) during the different test flights to obtain reliable information about the expectable change of aircraft behavior. A detailed description of e.g. the three SLD-ice configuration flight tests is given in Ref. [7]. FIG. 7 shows lift and drag curves from aerodynamic model evaluations after identification from flight data with five different icing configurations (two App. C and three App. O). It is clearly visible, that the different types of icing have a specific influence on the aircraft aerodynamics.
FIG. 8 provides results from the flight performance evaluation with different ice configurations based on the models identified from flight test data: the results are well comparable to the flight performance degradation shown in FIG. 4. This example reveals that some ice shapes significantly restrict the aircraft's safe envelope. The icing-induced change of flight dynamics is strongly dependent on the specific ice shapes. TAB. 1 contains an overview of results for the Phenom 300 dynamic mode changes with the different ice configurations. The detailed results of this research are given in e.g. Refs. [5–9] with a more specific view on the individual effects of different ice shapes on the aircraft flight performance and flight dynamics. Furthermore, one additional goal of this cooperation was to develop new system-identification methodologies to monitor the icing degradation online and directly identify aircraft simulation models containing the icing-related degradations in-flight [7, 8].

4. PERFORMANCE-BASED ICE DETECTION

The knowledge about the significant drag increase and therefore flight performance degradation caused

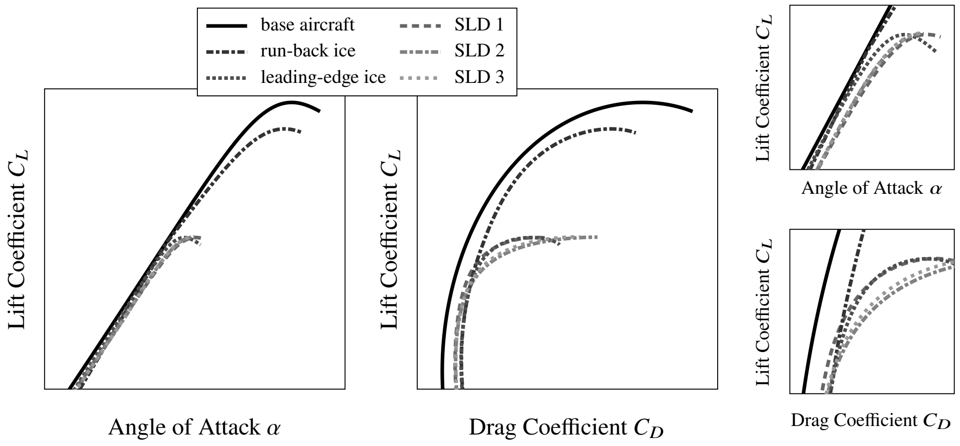

FIG 7. Phenom 300 lift and drag curves from model evaluation after identification from flight data; different icing configurations with certain regard on SLD configurations; right hand side: zoom plots for medium lift coefficients.

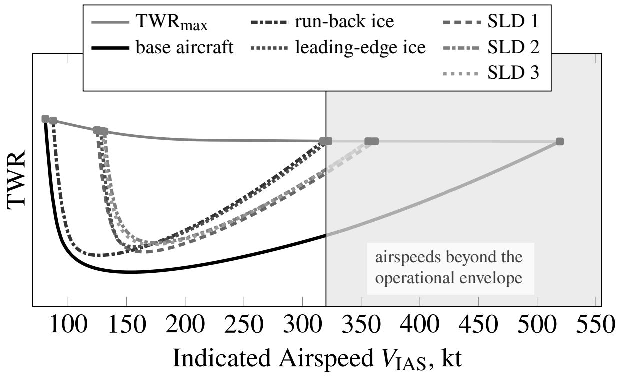

FIG 8. Example of Phenom 300 flight performance evaluation with different ice shapes: indicated airspeed V_{IAS} vs. thrust-to-weight ratio TWR; from [6]

	run-back	leading-edge	SLD 1	SLD 2	SLD 3
		phugoid			
damping	⇑	⇑	⇑	⇑	⇑
		short period			
damping	↑	↑	↑	↑	↑
natural frequency	↓	↑	⇓	↓	↓
		Dutch roll			
damping	⇑	⇑	↓	⤢	⤢
natural frequency	↓	↑	↑	⤢	⤢
		rolling motion			
time constant	↓	↓	↑	⤢	⤢
		spiral motion			
time constant	stabilized		↓	⤢	⤢

TAB 1. Change of Phenom 300 dynamic modes for different ice configurations: ⇑ strong increase, ⇓ strong decrease, ↑ increase, ↓ decrease, ⤢ change of root locus.

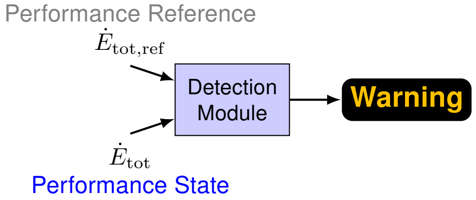

FIG 9. Basic principle of the performance-based ice detection method; from [11].

by ice accretion on airplanes raised the idea to utilize this effect for “indirect ice detection”. As a result of the work in the SuLaDI-project, a novel methodology for such a detection of icing-related aircraft performance degradation was developed [10,11] and patented [12]. The basic principle of the methodology is shown in FIG. 9: the power imbalance $\dot{E}_{\mathrm{tot}}$ with respect to the surrounding air is calculated and compared to a given reference in order to detect the abnormal flight performance. A verification study was conducted in 2016 and simulator trials with airline pilots in DLR’s full motion Airbus A 320 simulator AVES revealed the high benefit of this detection strategy for aircraft operations.

5. HORIZON 2020 PROJECT SENS4ICE

In 2019, the ongoing research on icing lead to the EU Horizon 2020 project SENS4ICE (“SENSors and certifiable hybrid architectures for safer aviation in ICing Environment”)[1] [13]. With this project, the cooperation between DLR and Embraer was continued, as Embraer is one of the 19 international partners of the international project. The SENS4ICE project provides a novel approach which seeks to intelligently cope with the complex problem of ice detection through the hybridization of different detection techniques. In the hybrid system, the direct sensing of atmospheric conditions and/or ice accretion on the airframe is combined with the indirect detection of ice accretion on the air-

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[1] grant agreement N°824253, duration 2019 to 2023, `https://www.sens4ice-project.eu/`

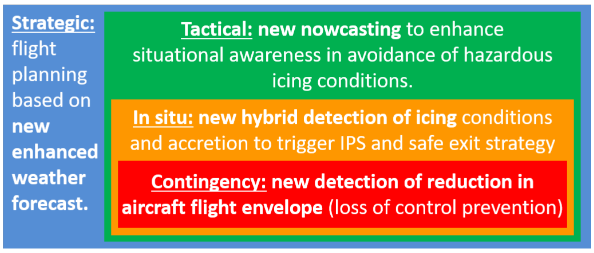

FIG 10. SENS4ICE layered safety concept for liquid water icing

frame based on the related aircraft flight performance degradation. SENS4ICE addresses the development, test, validation, and maturation of the different detection principles, the hybridization – in close cooperation with regulators to develop acceptable means of compliance – and the final airborne demonstration of technology capabilities in relevant natural icing conditions. FIG 10 shows the unique layered concept to address the challenge of liquid water icing detection. A combination of technologies to detect icing conditions in the atmosphere, ice accretion on the aircraft's surfaces, or the change of aircraft characteristics due to ice accretion are part of the hybrid solution. All in all, the hybrid system will combine several individual technologies with the aim of providing a more robust and reliable detection.

6. FUTURE RESEARCH

In aviation, new technologies and markets evolved in the recent years: unmanned aerial vehicles of different sizes and for various applications came more into focus of academia and industry. Therefore, it is planned to transfer the already existing knowledge about airplane icing from large transport airplanes to other types of vehicles and focus the upcoming research activities e.g. to the new challenges of drone operations in icing environments.

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