Novel Ice Detection Methodology and System for Safer and Greener Aviation

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Greener Aviation 2016
Oct. 11th 2016
Brussels, Belgium
Outline

• Motivation

• Feasibility of an ice detection system based on the aircraft performance (operational flight data)

• Overview of the proposed detection methodology

• Results in simulation

• Summary and outlook
Motivation

- Hazardous effects of ice accumulations caused various accidents in the past

- Goal: **early detection of ice accumulations**
  - Providing necessary information to maintain safe flight conditions
  - Enabling more selective activation of anti-ice systems with reduced energy consumption

- Requirements:
  - Reasonable impact on operating costs
  - If possible, retrofit capability

**Reduced impact of icing on aviation safety and better use of current anti-ice systems**
Feasibility of an Ice Detection System Based on the Aircraft Performance: Basic Principle

Change of lift (resp. pitching moment) coefficient derivatives ($C_{L\alpha}, C_{m\alpha}$)

+ Almost fully conserved within linear dynamic models
  ➔ direct use of the tools from the linear control theory possible

- Also significantly impacted by other phenomena
  ➔ not specific enough

- Excitation needed for proper detection
  (steady flight is an issue)

Change of drag polar (glide ratio)

Remark: Information lost during linearization

+ Seems to characterize very well the effects of ice accretion
  (variation under real conditions due to all kinds of other effects validated with a data-mining approach on FDR data)

+ Detection during steady flight conditions
Performance-Based Detection of Icing

\[
\Delta C_D \approx \frac{\dot{E}_{tot,\text{ref}} - \dot{E}_{tot}}{V_{TAS} \cdot \bar{q} \cdot S_{Wing}}
\]

Is the filtered equivalent additional drag above the detection threshold?

Performance Reference
\[ \dot{E}_{tot,\text{ref}} \]

Detection Module

Warning

Performance State
\[ \dot{E}_{tot} = V_{TAS} \cdot \dot{V}_{TAS} \cdot m_{AC} + \frac{1}{2} \cdot V_{TAS}^2 \cdot \dot{m}_{AC} + g \cdot \dot{H} \cdot m_{AC} + g \cdot H \cdot \dot{m}_{AC} \]
Feasibility of an Ice Detection System Based on the Aircraft Performance: (Big) Data Analysis

• Questions:
  How large is the performance variation that can be observed within a complete fleet during regular airline operations? (Incl. sensor errors & calibration)
  Can an ice detection system based on performance be reliable?

• Challenges related to this particular data set
  • Data discretization and quantization
  • Missing engine thrust model
  • Data were partly anonymized
    • Flight ↔ Aircraft relationship unknown
    • No possibility to track a particular aircraft over time in order to identify effects related to maintenance
  • For the B737-800 several winglet configurations are mixed in the data

• Some of the information (e.g. engine thrust data) could be deduced from the large amount of data
  → Allowed to reduce the dispersion that was not directly linked to the ice effects or the sensor properties
Feasibility of an Ice Detection System Based on the Aircraft Performance: Data Segmentation

1 segment with quasi-steady engine state found → 1 performance data point
Feasibility of an Ice Detection System Based on the Aircraft Performance: Performance Variation

Boeing 737-700: 23,842 data sets with 202,797 flight data segments

Boeing 737-800: 51,847 data sets with 5,161,814 flight data segments
Overview of the Proposed Detection Methodology

- \( V_{\text{TAS}} \)
- \( H \)
- \( \bar{N}_1 \)
- \( n_{z,a} \cdot m_{\text{AC}} \)
- \( \ldots \)

Data Conversion & Wind Estimation

Evaluation of Performance Reference Model

- \( \dot{E}_{\text{tot,ref}} \)
- \( \delta_{\text{Detection}} \)

Aircraft Configuration

Additional Terms for Compensation

Flight Point Information

Determination of Current Performance

- \( \dot{V}_{\text{TAS}}, \dot{V}_k \)
- \( V_{\text{TAS}} \)
- \( H \)
- \( \dot{H} \)
- \( m_{\text{AC}} \)
- \( \dot{m}_{\text{AC}} \)

Detection Module

MCI
Overview of the Proposed Detection Methodology

- Dealing with turbulence
  → Wind estimation (Kalman filter) + low-pass filtering

- Dealing with wind change (downburst, wind shear, …)
  → Wind estimation (Kalman filter) + correction of the kinetic energy rate

\[ \dot{E}_{\text{tot,corr}} = V_{\text{TAS}} \cdot \dot{V}_{\text{TAS},\hat{V}_k} \cdot m_{\text{AC}} + \frac{1}{2} \cdot V_{\text{TAS}}^2 \cdot \dot{m}_{\text{AC}} + g \cdot \dot{H} \cdot m_{\text{AC}} + g \cdot H \cdot \dot{m}_{\text{AC}} \]

- Dealing with sideslip even if performance models do not include sideslip effects

\[ \Delta C_D (\beta) = \frac{\dot{E}_{\text{tot,ref}} - \dot{E}_{\text{tot,corr}}}{V_{\text{TAS}} \cdot \bar{q} \cdot S_{\text{Wing}}} - \Delta C_D \beta,\text{comp} \]

\[ \Delta C_D \beta,\text{comp} = - \frac{n_y \cdot m_{\text{AC}} \cdot g \cdot \sin \beta}{\bar{q} \cdot S_{\text{Wing}}} \]
Results

Detection of icing with no excitation (steady state flight)
• Slow accretion of ice and slow restoration of original performance
  
  Good = detection

Check for false alarms
• In the presence of turbulence and wind shear
• During steady sideslip
• During dynamic maneuvers
  
  Good = no false alarm (i.e. no detection)
Results – Slow Accretion of Ice and Slow Restoration of Original Performance

- Real power imbalance stays at zero due to the autothrust and autopilot (speed and altitude remain constant → total energy remains constant)

- But the reference model predicts a positive power imbalance

⇒ Difference between both leads to trigger the detection as expected
The combination of turbulence and wind shear causes significant changes in energy.
The wind estimation filters the turbulence out.
The corrected power imbalance corresponds to the prediction made thanks to the performance model.

\[\text{no false detection}\]
Constant sideslip of 10 degrees is held (with steady heading).

The real energy remains constant (constant speed and altitude).

But the model (with no sideslip effect) predicts that the AC should gain energy (positive power imbalance),

\[ \rightarrow \]  leads to an equivalent drag increase well above the detection threshold.

However, the proposed compensation term is almost equal to the computed equivalent drag increase,

\[ \rightarrow \]  No false detection, thanks to the compensation term.
Results – Behavior During Dynamic Maneuvers

Series of maneuvers on all axes (in direct law):
- Good match in power imbalance (observed vs. model) due to pitch maneuvers
- Large deviations with sideslip
  - but here again the compensation term is precise enough
  - no false detection
Summary and Outlook

- Presented a novel ice detection methodology:
  - Based on the sensors already installed on current aircraft
  - Work during steady flight but also behaves correctly during maneuvers
  - Definition of threshold for the whole envelope made very easy through the use of a normalized “equivalent increase of the drag coefficient”

- Fine tuning of threshold values for specific requirements still to be done (trade-off between detection sensitivity and probability of false alarms)

- Sensitivity to measurement uncertainties is currently being performed and will be published soon (probably at AIAA Aviation 2017)

- Current work on the associated HMI and cockpit procedures

- Hybridization with other ice detection systems? (to enable better trade-offs between reliability and sensitivity)

- Patent pending on the method and the system

- Maturation ideally in cooperation with aircraft manufacturers and operators