Academic Airframe Icing Perspective

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Introduction

• What research do we need?
  – 3-D Ice accretion and aerodynamics
  – Systems-based multidisciplinary research

• But first:
  – Some philosophy on university research
  – Some icing research history and lessons learned

• Then to 3-D and multidisciplinary research
Why University Research?

• The best university researcher strives to have **Impact** in many dimensions:
  – New discoveries
  – Graduate education
  – Contribution to society
  – Economic development

• University researchers think of research in MS and Ph.D “units”

• University research can be both applied and fundamental
Basic versus Applied Research

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- Traditional Research Continuum

- Quadrant Model of Research

From “Pasteur’s Quadrant” by Donald E. Stokes

Feasibility: Yes

Feasibility: No

Quest for Fundamental Understanding?

Yes

No

Consideration of use?

Yes

No

Pure basic research (Bohr)

Use-inspired research (Pasteur)

Pure applied research (Edison)

From “Pasteur’s Quadrant” by Donald E. Stokes
2-D Airfoil Icing Aerodynamics

NASA/university 2-D iced-airfoil aerodynamics

• Evolving goals as we learned more and motivation changed (1980 – 2008)
  – Understanding of ice accretion effect on lift and drag
  – Support for CFD development and validation
  – Understand iced-airfoil physics
  – Roselawn accident focused us on “use”
  – Aircraft control and more 3-D
  – Effect of airfoil and ice-shape geometry
  – Understanding Re and M effects
  – Ice accretion aero classification and simulation
Aerodynamic Techniques

Initial techniques
• Relatively simple steady RANS
• Simple small-scale experiments with large horn ice at low Re

Current techniques
• 3-D unsteady RANS/LES methods
• Pressure tunnels at near-flight Re and M, multiple ice shapes, advance measurement techniques including PIV
What did we learn from 2-D aerodynamics?

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Process

• Re and M important to understand but low-Re data are valuable and provide a cost-effective research method for many cases

• Flowfield understanding critical in reducing “matrix” and understanding simulation

• Flow separation is key and is always unsteady and 3-D

• Roselawn and considering “use” or application led to more focused and productive research programs

Physics

• An understanding of the basic relationships between airfoil geometry, ice-accretion geometry, and iced-airfoil aerodynamics and aerodynamic performance including control was accomplished with some fundamental understanding of the flow

![Diagram of flowfield with labels: Shear Layer, Vortex Shedding, Recirculation Region, Reattachment Zone, and \( V_\infty \)]

Gurbacki^{22}
2-D Icing

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- **Ice Accretion Physics**
  - Droplet trajectory calculations well understood
  - Basic surface water transport and bulk ice growth is understood
  - LEWICE does a good job within its 2-D validation data set

- **Iced-Airfoil Aerodynamics**
  - Understand basic flowfield and gross aerodynamics for the four identified ice shape categories
  - Simulation ice shape methods identified and validated
  - RANS does a reasonable job with gross aerodynamics
The 3-D Icing Problem

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- **Ice accretion**
  - 3-D ice accretion have been observed and documented
  - Scallops have been studied, resulting in a foundation of experimental understanding
  - Fundamental processes in 3-D are not understood well enough for reliable models

- **Aerodynamics**
  - Flow separation including shear layer development is the fundamental flow feature and it is 3-D and unsteady
  - RANS insufficient but full 3-D and unsteady cost/resource prohibitive
  - No 3-D experimental data at near-flight Re and M
3-D Ice Accretion

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• **Goals**
  – Understand basic physical processes underlying aircraft icing.
  – Create simplified engineering tools.
  – Understand the accuracy of the engineering tools.

• **What is needed?**
  – Growth mechanisms for complex 3-D accretions (scallops, etc.)
  – Simulation methods for complex 3-D accretions
  – Nonlinear coupled interactions (droplets splashing, surface water transport, impact freezing, etc.)
3-D Ice Accretion (cont.)

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Approach

• Understand the basic physical processes underlying aircraft icing:
  – Develop a foundation of understanding based on experiments.
  – Develop detailed physical models which explain the experiments.

• Use icing physics knowledge to help create simplified ice accretion engineering tools.

• Understand the processes which limit the accuracy of the engineering tools.
Example – Surface Physics

- Basic water transport can be handled using simple models.

- Ice surface roughness can be explained by heat transfer driven instability of the ice surface.

- There is a need to better understand more complex 3-D nonlinear interactions:
  - Growth of complex ice shapes.
  - Nonlinear coupling of droplet impacts, unsteady aerodynamics past complex 3-D ice/water shapes, water transport, and complex ice growth. Coupling to rapid phase transitions when crossing from rime to glaze icing, etc.

- NASA VIST facility and icing physics experiments are important steps to resolve these issues.

Source: Rothmayer, Matheis, Otta, Tsao, Wang
3-D Icing Aerodynamics

**Goals**
- Basic understanding of 3-D iced wing flowfield
- Simulation methods and a small-scale, low-Re capability
- Computational methods that accurately predict $C_l_{\text{max}}$ and control deflection effects

**What is needed?**
- Iced-wing data at high Reynolds number and flight $M$
- Data for code development and validation
- Unsteady, RANS/LES method development
- Key features: unsteady separated flow, shear-layer development, transition
3-D Icing Aerodynamics

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- **Approach**
  - Fundamental studies to aid understanding of key flow phenomena
  - Development of advanced CFD methods
  - High-Re data on representative geometries
  - Validation of CFD methods
  - Experimental and computational tools for practical problems
Example – Hybrid RANS/LES

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- **Observations**
  - RANS, while highly efficient, requires a high degree of phenomenological modeling, which limits its applicability
  - LES, which models fewer of the turbulent scales, is prohibitively expensive in aero boundary layers

- **Current general consensus**
  - Valid for massively separated flows
  - Problematic for aerodynamically-relevant flows

**Basic idea**
- Use RANS in regions of attached flow
  - Consistent with modeling the Reynolds stress
- Use LES in regions of separated flow
  - Consistent with modeling the subgrid stress
- Implicit zonal boundary
  - Achieved through a dynamically-varying eddy viscosity

**DES for extruded GLC305/944 ice shape**

- Selected time steps show development of characteristic “loop” vortices
Example – Hybrid RANS/LES

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- DES for extruded GLC305/944 ice shape
  - Detached Eddy Simulation (DES) (specific form of hybrid RANS/LES)

Three-dimensional unsteady flow in separated region

RMS of streamwise velocity fluctuations

Source: Mogili, Thompson (MSU), Choo, and Addy (NASA GRC)
Systems-based Multidisciplinary Research

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- **Example – Smart Icing Systems**
  - Combined human factors, controls, flight mechanics, and aerodynamics to address icing flight safety system
  - Systems to sense effect of ice accretion on aircraft and operate IPS, provide envelope protection, inform/advise pilot, etc
  - Systems, multidisciplinary approach provides integrated solutions and where needed helps guide new research
• **Needed Multidisciplinary Research**
  
  – Couple ice accretion and ice protection modeling with aerodynamics and control
  
  – Couple flight mechanics, aerodynamics, sensing and flight mechanics and control
  
  – Bring atmospheric science and route planning into the problem of SLD protection
  
  – Include Human Factors and training into the research with flight simulation, ice accretion, and flight dynamics
  
  – Etc.
Summary

2-D ice accretion and aerodynamics reasonably well understood for engineering applications.

To significantly improve our current capabilities we need to understand 3-D:
- Important ice accretion physics and modeling not well understood in 3-D
- Aerodynamics unsteady and 3-D especially near stall

Larger systems issues important and require multi-disciplinary team approach.