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Iced-airfoil aerodynamics

M.B. Bragg*, A.P. Broeren, L.A. Blumenthal

Aerospace Engineering, College of Engineering, University of Illinois at Urbana-Champaign, 306 Talbot Laboratory, MC 236, 104 South Wright Street, Urbana, IL 61801-2935, USA

Abstract

Past research on airfoil aerodynamics in icing are reviewed. This review emphasizes the time period after the 1978 NASA Lewis workshop that initiated the modern icing research program at NASA and the current period after the 1994 ATR accident where aerodynamics research has been more aircraft safety focused. Research pre-1978 is also briefly reviewed. Following this review, our current knowledge of iced airfoil aerodynamics is presented from a flowfield-physics perspective. This article identifies four classes of ice accretions: roughness, horn ice, streamwise ice, and spanwise-ridge ice. For each class, the key flowfield features such as flowfield separation and reattachment are discussed and how these contribute to the known aerodynamic effects of these ice shapes. Finally Reynolds number and Mach number effects on iced-airfoil aerodynamics are summarized.

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*Corresponding author. Tel.: +1 217 333 2651; fax: +1 217 244 0720.
E-mail address: mbragg@uiuc.edu (M.B. Bragg).

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1. Introduction

Icing research began in the late 1920s and early 1930s, but it was not until WWII that icing tunnels were built and icing was seriously addressed in response to the war effort. From this time until the start of the modern icing research program in 1978 at NASA Glenn (then Lewis) Research Center, the focus of aerodynamic research was to measure the effect of ice on the lift and drag of airfoils or the overall aircraft performance parameters. This was summarized by the Gray correlation [1] for iced-airfoil drag in 1964 and the well-known plot of Brumby [2] in 1979 that compiled the known data of the time to present empirical curves of maximum lift loss versus roughness size and location.

With the NASA aircraft-icing program that was initiated in 1979, computational fluid dynamics (CFD) began to be developed and applied to the prediction of aerodynamic performance of airfoils with ice. To support this work, iced-airfoil aerodynamics research was initiated to provide detailed aerodynamic data for use in code validation and experimental results including the first flowfield measurements. This began to appear in the literature in the mid 1980s. These data, and the corresponding CFD calculations, provided the first glimpse of the flow physics of iced-airfoil aerodynamics. Ice-induced separation bubbles were found to dominate the flowfield and the aerodynamic performance in many important cases.

In 1994 the Roselawn ATR-72 accident reinforced the importance of icing aerodynamics research and changed its focus from a scientific exercise to one clearly focused on aircraft safety. This included motivating the experimental and computational investigation of different types of ice accretions including supercooled large-droplet (SLD) shapes and intercycle ice shapes. Partly in response to the need for better criteria for selecting "critical ice shapes", some of the most detailed parametric studies of ice shape and airfoil geometry effects on airfoil and wing aerodynamics have recently been completed. Significant insight has been gained into iced-airfoil and wing aerodynamics as a result of this aircraft safety motivated research.

After an expanded version of the above historical review, this paper presents an overview of our current understanding of iced-airfoil aerodynamics. Lynch and Khodadoust [3] have provided an excellent and exhaustive review of the effect of ice accretion on aircraft aerodynamics. In their report, they assess the effect of ice on performance parameters such as lift and drag using available test results and correlate these data in ways useful to aircraft designers and others. The present paper attempts to take a different, complementary approach, by providing insight into the flow physics that cause the integrated aerodynamic effects. Experimental results will be summarized to address: how ice roughness affects aerodynamics; the effect of leading-edge horns and the accompanying flowfield; the aerodynamics of spanwise-ridge shapes due to SLD, runback and intercycle ice; the relationship between airfoil geometry and iced airfoil aerodynamics, etc. Additional topics such as three-dimensional (3D) effects, unsteady phenomena near stall, ice simulation effects, and Reynolds number and Mach number effects will also be discussed.

The intent of this paper is to present a brief review, and as a result space did not permit the presentation and discussion of all the research that deserves to be included in a thorough review of this topic. The discussion of the physics of iced-airfoil flowfields that follows the review is also invariably flawed as is any review of an active research area. This paper summarizes briefly our current understanding, but as research continues, areas where our understanding is poor or incomplete will hopefully be made clearer in the coming years.

2. Literature review

The purpose of this literature review is not to provide an exhaustive survey of icing aerodynamics research, but to review some of the research known by the authors to be significant and representative of the research of the period. The review includes added details as we discuss the recent work that is more focused on ice accretion flowfield physics. These studies are the most relevant to the objectives of this paper.

2.1. Icing aerodynamics research up to 1978

In this time period aircraft icing was seen as an operational problem and the research focus was on measuring the effect of ice on lift and drag, and sometimes control. The research was almost exclusively experimental with occasional analytical attempts to develop simple relationships to predict ice accretion effects.

Carroll and McAvoy [4] reported in 1929 on the National Advisory Committee for Aeronautics (NACA) program to study ice formation on airplanes. Ice accretion shapes from a VE-7 aircraft are reported and they recognized that aerodynamic penalties due to ice were a more severe hazard than the additional weight. Methods of ice protection are discussed, but the article "recommends avoidance of conditions under which this (ice formation) is most likely to occur".

Research on the aerodynamic effects due to surface roughness and protuberances [5,6] began in the 1930s. These and similar studies identified the leading edge as the most sensitive region for surface roughness. In 1938, Gulick [7] tested an aspect ratio 6 wing in the Langley Full-Scale Tunnel with roughness intended to simulate