Aerospace Science and Technology 109 (2021) 106417

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Large-eddy simulations of complex aerodynamic flows over multi-element iced airfoils

Young Mo Lee [a], Jae Hwa Lee [a,b,*], Lawrence Prince Raj [c], Je Hyun Jo [d], Rho Shin Myong [b,d]

[a] Department of Mechanical Engineering, Ulsan National Institute of Science and Technology (UNIST), 50 UNIST-gil, Eonyang-eup, Ulsan 44919, Republic of Korea
[b] Research Center for Aircraft Care Technology and ReCAPT, Gyeongsang National University, Jinju, Gyeongnam 52828, Republic of Korea
[c] Department of Aerospace Engineering and Applied Mechanics, Indian Institute of Engineering Science and Technology, Shibpur, Howrah-711103, West Bengal, India
[d] School of Aerospace and Software Engineering, Gyeongsang National University, Jinju, Gyeongnam 52828, Republic of Korea

ARTICLE INFO

Article history:
Received 24 April 2020
Received in revised form 8 November 2020
Accepted 4 December 2020
Available online 17 December 2020
Communicated by Yu Lv

Keywords:
Large-eddy simulation
Multi-element iced airfoil
Aerodynamics

ABSTRACT

Large-eddy simulations (LESs) of flows over two types of iced airfoils with three multi-elements are performed to investigate the aerodynamic characteristics and complex interactions between flows generated from slat, main, and flap elements. The two iced airfoils are considered under supercooled large droplet (SLD) and non-SLD conditions. A good agreement of the mean properties between our numerical and previous experimental data demonstrates that our LES method provides an accurate solution of the complex flows around iced airfoils., whereas it is not for unsteady Reynolds-averaged Navier–Stokes (URANS) data that is simulated independently. For the iced airfoils under the SLD and non-SLD conditions, the aerodynamic degradation is found compared to that of a clean airfoil because the separation bubbles (SBs) induced by ice accretion change shear layer (SL) trajectory shed from the slat cusp, leading to a severe reduction in mass flow. Furthermore, we show that the flow interactions near the slat gap play a crucial role in determining the flow characteristics on main and flap elements (e.g., flow separation). Although strong flow interactions are observed for the non-SLD case because of the presence of upwind horn-shaped ice, the smaller gap distance of the SLD case leads to a larger lift loss. The unsteady features of SBs on the upper surfaces of the slat and main elements under the non-SLD condition are characterized by the power spectral density (PSD) of the pressure fluctuations with multiple peaks at low and high frequencies.

1. Introduction

The supercooled water droplets available in clouds can result in ice accretion on the surfaces of aircrafts and engines when an aircraft flies at subfreezing temperatures. The ice accretion shapes are affected by atmospheric temperature, liquid–water content (LWC), median volume diameter (MVD) of droplet, flight speed, and phase of flight, and the accreted ice leads to a severe reduction in lift, increased drag, and aircraft instability [1–4]. Furthermore, the droplet diameter is known to have strong influence on the amount, location, and shape of the ice accretion [5–7]. In the aviation community, the droplet diameter in the range of 40 μm or less has been considered for certification (FAA Appendix C). However, in some atmospheric conditions the droplet size may reach 40 μm to 400 μm, which is known as a supercooled large droplet (SLD). Hence, in 2014, a new certification regulation is added (Appendix O) along with the present regulations (Appendix C) to address the effect of SLD icing conditions. Because an investigation of ice shapes generated under various conditions along with aerodynamic performance is essential for the certification process and ice protection system design, it is valuable to study the effects of icing on the aerodynamics around various iced airfoils.

For several decades, much effort has been devoted to the study of flows around single-element iced airfoils [1,8–11]. However, since modern aircraft usually use multi-element wings to attain high lift at a high angle of attack (AOA) and low speeds [12], recent studies have examined the effects of ice accretion on multi-element airfoils with a supercooled large droplet (SLD) greater than 40 μm and/or a non-SLD smaller than 40 μm. In the NASA Lewis Icing Research Tunnel (IRT), Shin et al. [13] analyzed the effects of droplet size on a multi-element airfoil under a non-SLD condition. They employed two median volume diameters (MVDs) of 20 and 25 μm and showed that the icing limits generated with

* Corresponding author at: Department of Mechanical Engineering, Ulsan National Institute of Science and Technology (UNIST), 50 UNIST-gil, Eonyang-eup, Ulsan 44919, Republic of Korea.

E-mail address: jhlee06@unist.ac.kr (J.H. Lee).

https://doi.org/10.1016/j.ast.2020.106417
1270-9638/