Cold Regions Science and Technology 115 (2015) 64–76

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Laser scanning applied for ice shape measurements

Xiaoliang Gong [a],*, Stephan Bansmer [b]

[a] National Key Laboratory of Science and Technology on Aerodynamic Design and Research, Northwestern Polytechnical University, Xi'an 710072, PR China
[b] Institute of Fluid Mechanics, Technische Universität Braunschweig, Braunschweig 38108, Germany

ARTICLE INFO

Article history:
Received 13 August 2014
Received in revised form 9 February 2015
Accepted 18 March 2015
Available online 31 March 2015

Keywords:
Laser scanning
Ice
Shape measurement

ABSTRACT

We proposed a 3-D ice shape measurement technique through laser light sheet scanning. The method was first verified on a plastic frustum which was printed by a 3-D rapid prototyping printer. Then, the method was further verified on a clear ice frustum that was made by mold and casting from the plastic frustum. To increase reflectance of clear ice, a thin layer of frost was grown on the ice surface. Both results show good agreement with true data. At last, the method was utilized to measure and digitize the temporal evolution of rime ice shapes and the final mixed ice shape on the leading edge of a NACA 0012 airfoil in an icing wind tunnel. The measurement at the end of ice accretion was compared with hand trace results. Results are very promising for future ice growth measurements in icing wind tunnels.

1. Introduction

1.1. Background

Since the very beginning of the aviation industry, the icing problem has already been one of the most serious weather hazards facing airplanes. According to studies, the icing problem on an airfoil reduces lift by 30% while increasing drag by 40% or even more (Bragg et al., 2005; Czernkovich, 2004). In particular, the changed stall characteristics impose a serious safety threat. That is the reason why icing research started soon after the invention of aircrafts in the early 20th century. A large amount of experimental and numerical research has been carefully and thoroughly carried out (Bragg et al., 2005).

The usual process of ice accretion is when supercooled water droplets impinge upon a surface where the total air temperature is below freezing (Czernkovich, 2004). Depending on whether liquid water freezes immediately or not, ice is categorized into rime ice and clear ice (also known as glaze ice). Rime ice forms when water droplets impacting a surface freeze on contact while clear ice forms when water droplets do not freeze immediately on impact. The unfrozen water runs back and freezes afterwards which can create smooth, transparent shapes that are complicated.

1.2. Measurement of ice shapes

At present, there are mainly three methods to measure ice shapes in icing wind tunnels. The most typical method used is probably cross-section tracing (also known as hand tracing) (Addy and Lee, 2009; Addy et al., 1997; Lee et al., 2012). This procedure for documenting ice shapes is done by first melting a slot in the ice using a heated knife or plate, perpendicular to the test model surface (see Fig. 1(a)). Then, a cardboard template that conforms to the model surface is inserted or a small ice sample is taken down and put on a piece of paper. At last, the ice shape is traced by hand using a pencil or a pen (see Fig. 1(b)). The traced ice contour normally has to be digitized subsequently (see Fig. 1(c)). While this method is so simple that it exists in almost every paper regarding ice shape measurements, there are four major inherent disadvantages. The first drawback is variations in results due to human error, individual habit, and digitization procedure (Wright, 1999). The second problem is that as a contact measurement, the tracing technique probably melts or breaks off the ice, especially for tracing small ice features far aft of the main ice shape (Miller et al., 2005). Worse yet, it interrupts ice accretion. After each measurement, the ice then has to be cleaned off the model, the tunnel has to be cleared, and ice has to accrete for the next test run. That makes it extremely difficult to study the temporal ice growth throughout an exposure to icing conditions. The third disadvantage is that the cross-section tracing gives only a 2-D contour at certain locations of a 3-D ice shape. But even with a 2-D model, ice shapes are not ideally uniform along the spanwise direction due to the randomness in droplet impingement combined with turbulent heat transfer during ice accretion (Cook, 2000; Wright, 1999). For 3-D swept wing models, the ice shapes are even more complex. The crossflow induces so called scallops (Vargas, 2007). The last flaw of tracing is that it cannot pick up fine ice structures such as initial accretion or details of the gross ice shape. Those fine structures are known to be roughness elements, which are aerodynamically important in some cases (Bragg et al., 2007). The attempt to simulate 3-D ice shape effects by adding appropriate roughness to a 2-D tracing has proven to be very difficult without advance knowledge of the

---

* Corresponding author. Tel.: +86 29 88494356.
E-mail address: xlianggong@gmail.com (X. Gong).

http://dx.doi.org/10.1016/j.coldregions.2015.03.010
0165-232X/

(a) Inserting heated plate (b) Tracing ice profile (c) Digitizing hand trace

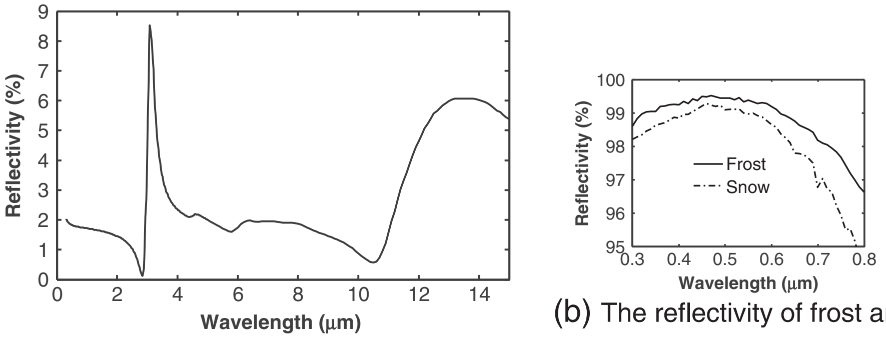
Fig. 1. Hand tracing process.

accretion aerodynamics (Busch et al., 2008). A similar method with hand trace is 2-D photography which records the cross-sectional view of ice accretion together with a dimension reference object after the ice is cut by a heated plate as mentioned ahead (Han et al., 2011). The major error of 2-D photography results from the inclined perspective, the desired plane being out of focus, and ice out of the desired plane being recorded.

The mold and casting method developed at NASA Glenn is currently accepted as a high accurate technique for recording ice shapes (Reehorst and Richter, 1987). First, a mold is made directly from ice accretion in the icing wind tunnel. Then, artificial ice accretion is cast from the mold. This method maintains nearly all the three-dimensionality and surface details of ice. This technique generates valuable benchmark for icing research (Broeren et al., 2010, 2011; Papadakis et al., 2005). However, it is an expensive process that may not be affordable for large-scale experiments, which makes this method unpractical in many cases considering also that both molding and casting is time consuming (Addy et al., 1997). This procedure also suffers from the same problem as cross-section tracing does: it is a contact measurement, damaging original ice, and can only be done once at the end of every tunnel run. Thus, mold and casting is incapable of documenting the whole icing process continuously from the initial roughness to the final accretion.

There have been several studies that have captured some quantitative information by photographs. Anderson obtained roughness element diameters and smooth-zone widths from recorded images (Anderson et al., 1998). But the work relied solely on human eyes to find roughness element edges, inferred from the light and dark patterns in images, which was very subjective. Therefore, the results could differ considerably from one researcher to another. Furthermore, the photogrammetry used by Anderson was actually a 2-D technique. As the model curves away from the camera lens, the roughness element diameter gets larger in the spanwise direction than in the chordwise direction (Anderson et al., 1998). McKnight measured ice shapes by stereo photographs during flight (McKnight et al., 1986). It was the first time photogrammetry was applied to in-flight quantitative icing research. Even a satisfactory spatial accuracy was achieved, but the final result was merely a 2-D ice shape profile which was composited from selected ice surface points. This claimed accuracy applied only to rime ice rather than clear ice whose surface was unidentifiable due to translucency or even transparency. As a matter of fact, the claimed accuracy for rime ice is also open to doubt since points on the ice surface in two stereo images were selected manually by magnifying images in order to catch more reliable features in white ice. Collier first introduced quantitative photogrammetry into ice shape measurements in an icing wind tunnel (Collier et al., 1999). In their work, a single camera was used and moved vertically to generate stereo photographs. Although Collier claimed that their method would capture three dimensional variations of ice shapes, only several 2-D profiles at the same cross-section were shown. And these results were not even validated. Beyond that, this paper almost did not resolve any tricky optical problems with ice such as rime ice's white surface without discernible patterns. Recently, Struk and Lynch measured ice thickness and growth rate by still and video images at the National Research Council of Canada Research Altitude Test Facility (Struk and Lynch, 2012). Images from cameras mounted on top of the test section were studied in their work. Ice thickness was obtained by detecting ice edges through defining a region of interest and threshold values of image intensities. With that, the growth rate of ice was acquired for the first time in icing research. But this method was actually a simple 2-D way whose accuracy depended almost entirely on whether the maximum ice growth occurs in imaging plane. Ice shapes were not measured in their work.

By far, it is clear that all these methods of measuring ice shapes suffer from some disadvantages. From above discussions, it would be very good if a method encompasses the following two properties. First, the



(a) The reflectivity of clear ice (b) The reflectivity of frost and snow

Fig. 2. The reflectivity of clear ice, frost and snow (directional (10°) hemispherical reflectance). Baldridge et al., 2009