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Eliciting a human understandable model of ice adhesion strength for rotor blade leading edge materials from uncertain experimental data

Ana M. Palacios[a], José L. Palacios[b], Luciano Sánchez[a,*]

[a] Departamento de Informática, Universidad de Oviedo, 33071 Gijón, Asturias, Spain
[b] Department of Aerospace Engineering, The Pennsylvania State University, University Park, PA 16802, USA

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ABSTRACT

The published ice adhesion performance data of novel "ice-phobic" coatings varies significantly, and there are not reliable models of the properties of the different coatings that help the designer to choose the most appropriate material. In this paper it is proposed not to use analytical models but to learn instead a rule-based system from experimental data. The presented methodology increases the level of post-processing interpretation accuracy of experimental data obtained during the evaluation of ice-phobic materials for rotorcraft applications. Key to the success of this model is a possibilistic representation of the uncertainty in the data, combined with a fuzzy fitness-based genetic algorithm that is capable to elicit a suitable set of rules on the basis of incomplete and imprecise information.

1. Introduction

Helicopter rotors are more susceptible to icing than fixed-wing vehicles. Rotors impact more super-cooled water particles per second than the rest of the fuselage. The higher collection efficiency of rotor airfoils makes them accrete ice at a higher rate than thicker fixed-wing airfoils. While fixed wing aircraft usually cruise at altitudes above icing conditions, rotorcraft vehicles operate in atmospheric conditions where super-cooled water particles are found. Ice accretion can be critically dangerous, as it can modify the vehicles aerodynamics, create excessive vibration, increase drag (Withington, 2010), and introduce ballistic concerns as thick ice layers sheds off.

1.1. Electro-thermal de-icing systems and ice-phobic coatings

To date, the only de-icing systems qualified by the Federal Aviation Administration are based on electro-thermal energy. Electro-thermal systems melt the ice interface between accreted ice and the leading edge erosion protection cap of the rotor. Such a system requires large amounts of energy (3.9 W/cm^2) and contributes to an undesired increase in the overall weight of the system and cost of the blade. The weight related to the required electrical power can be as large as 112 kg on a 4300 kg gross weight helicopter (Coffman, 1987; Zumwalt, 1985). Normally, a secondary electrical system with redundant, dual alternator features is required when installing electrothermal de-icing on helicopters (Coffman, 1987; Zumwalt, 1985). The thermal de-icing mechanism is turned on cyclically to limit power consumption or introduce excessive heating of the leading edge structure (which could cause composite delamination). Those areas not protected during de-icing continue to accumulate ice until the heating mats under that specific leading edge region are turned on. During some occasions, melted ice might flow to the aft portion of the blade (where there are no heating mats) to refreeze. Since the electro-thermal de-icing system sublimates the ice interface, ice shedding occurs under centrifugal loading. Released ice patches could reach up to 7.6 mm in thickness (Coffman, 1987; Zumwalt, 1985) and are a ballistic concern for some vehicles. The system relies on the thermal conductivity of isotropic materials that protect the leading edge of the blade from erosion. For this reason, electro-thermal de-icing is not ideal for new high erosion resistant polymer based leading edge protection materials because they have lower thermal conductivity than isotropic materials.

Due to mentioned drawbacks, particularly power generation, weight, and system cost constrains, medium and small size vehicles avoid the installation of electro-thermal de-icing systems, also limiting operation in icing environments. A passive ice-phobic coating that prevents ice formation would be the ideal solution to helicopter rotor blade ice accretion.

1.2. Variability of the experimental data for ice-phobic coatings

The search for ice-phobic materials for rotorcraft applications is ongoing. To quantify the ice adhesion performance of novel "ice-phobic" coatings, many researchers have attempted to measure

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* Corresponding author.
E-mail addresses: palaciosana@uniovi.es (A.M. Palacios), jlp324@psu.edu (J.L. Palacios), luciano@uniovi.es (L. Sánchez).

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the shear adhesion strength of ice to these materials. The published data varies significantly, even for isotropic materials, as it is shown in Table 1 (Brouwers, Peterson, Palacios, & Centolanza, 2011). In this table, "Freezer ice" is ice accumulated slowly on a substrate, while "impact ice" would be that formed as a body travels through an icing cloud at a certain velocity.

Impact ice better represents the physics involved in ice formation on helicopter rotors. Even though some authors have studied ice accretion and shedding with impact ice, critical icing conditions governing ice accretion physics are not reported. These conditions are: liquid water concentration (LWC) of the cloud, median volume diameter (MVD) of the super-cooled water droplets in the cloud, ambient temperature and impact velocity. It is also important to know the surface conditions of the coatings being tested, especially surface roughness. Scavuzzo and Chu (1987) have demonstrated the effect of surface roughness on ice adhesion strength. Surface roughness issues are particularly important for rotorcraft, which may operate in both erosive sand/rain environments and icing conditions. An eroded blade leading edge will have an effect on the shedding performance of the rotor. The discrepancies reported on ice adhesion strength testing are attributed to the different test procedures adopted, to the ice adhesion process, and to the variant environmental conditions triggered during shedding.

1.3. Rule-based empirical models of ice creation

Computer models of rotorcraft icing are based on empirical data that is gathered in experiments under controlled conditions. The numerical experiments that will be discussed in this work are based on experimental knowledge gained by the Vertical Lift Research Center of Excellence at the Pennsylvania State University. This center has developed a new icing facility for rotorcraft icing research (Palacios, Brouwers, Han, & Smith, 2010).

The creation of ice is influenced by different parameters, whose interrelationship is complex (see Section 2). Furthermore, the control that the experts exert over these parameters is not complete, and thus the experiments are not fully repeatable. Significantly different outcomes can be produced for the same set of controlling parameters and to our best knowledge there is not a reliable mathematical model relating the experimental conditions with the ice adhesion performance of novel "ice-phobic" coatings.

In this study a rule-based model of the experimental data is proposed, whose knowledge base is to be automatically obtained by means of a computer algorithm. This system inputs the environmental and icing conditions and predicts whether the coating is suitable or not, considering the shear adhesion strength of ice to this material. There are advantages related to the use a of rule-based model against a statistical decision system for the application at hand. To name some:

- A rule-based system has a human understandable structure comprising sentences of the type "IF the control parameters are in certain set, THEN the adhesion strength is [...]". By direct examination of the rules, the experts can gain knowledge about the coating that is not evident from the raw experimental data.
- The subset of rules taking part in every prediction is known. These rules can be tracked down to these experiments where they originated. Ultimately this allows for assigning a degree of reliability to each prediction.
- In case that the control parameters are much different from those of any past experiment, a rule-based system can produce the output "unknown response", while regression models will generate a possibly wrong extrapolation.

On the other hand, obtaining rules from data is a computationally hard problem (Cordón, Gomide, Herrera, Hoffmann, & Magdalena, 2004; Herrera, 2008; Kuncheva, 2000), which is further complicated by mentioned uncertainty in the data. In this paper, those decisions taken for solving this learning problem will be detailed:

- The use of fuzzy logic, as it reduces the complexity of the knowledge base (Cordón, 2001).
- A possibilistic representation of the uncertainty in the data, since it is better suited than stochastic models for "epistemic uncertainty" (Dubois & Prade, 1987). This is the variability that is not related to random deviations but to an insufficient knowledge of the parameters governing the experiment.
- The use of genetic algorithms for obtaining fuzzy rules from uncertain data (Palacios, Sánchez, & Couso, 2010; Palacios, Sánchez, & Couso, 2011; Sánchez, Couso, & Casillas, 2007; Sánchez, Couso, & Casillas, 2009).

In Section 2, the rotorcraft icing facility and shedding testing procedures developed by the Pennsylvania State University is introduced. The characteristics of available experimental data regarding shear adhesion strength of ice to material are shown in Section 3, along with the use of possibility distributions for representing the uncertainty in this data. In Section 4, the structure of the fuzzy rule based system is detailed along with an overview of a novel learning algorithm able to elicit a knowledge base from possibilistic data. Section 5 contains the experimental validation of the proposed system, whose outcomes are compared with that of real experiments, and also with subjective predictions taken by human experts in the field. In Section 6 the paper finishes with the concluding remarks.

2. Icing system model

The Vertical Lift Research Center of Excellence at the Pennsylvania State University has developed a new icing facility for rotorcraft icing research. Achieving an initial operational capability in November 2009, the Adverse Environment Rotor Test Stand (AERTS) is designed to generate an accurate icing cloud around test rotor. The AERTS facility is formed by an industrial 6 m by 6 m by 6 m cold chamber where temperatures between −25 °C and 0 °C can be achieved. The chamber floor is waterproofed with marine lumber covered by aluminum plating, and a drainage system in the perimeter of the room collects melted ice during the post-test

Table 1
Shear adhesion strength (SAT) for Aluminum with a temperature of −11 °C.

Author	Ice	Test	SAT-kPa
Loughborough and Hass (1946)	Freezer ice	Pull	558
Stallabrass et al. (1962)	Impact ice	Rotating instrumented beam	97
Itagaki (1983)	Impact ice	Rotating rotor	27–157
Scavuzzo and Chu (1987)	Impact ice	Shear Window	90–290
Reich (1994)	Freezer ice	Pull	896