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Critical considerations in the mitigation of insect residue contamination on aircraft surfaces – A review

Mariana Kok [a,b], Joseph G. Smith Jr. [c], Christopher J. Wohl [c], Emilie J. Siochi [c], Trevor M. Young [a,b,*]

[a] Department of Mechanical, Aeronautical and Biomedical Engineering, University of Limerick, Ireland
[b] Materials and Surface Science Institute, University of Limerick, Ireland
[c] NASA Langley Research Center, Hampton, VA 23681, USA

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ABSTRACT

Mitigation of insect residue contamination on next generation aircraft is vital for the commercial exploitation of laminar flow technologies. A review of the critical entomological, meteorological and aeronautical factors affecting insect residue accumulation on aircraft leading edge surfaces is herein presented. An evaluation of a passive mitigation strategy, namely the use of anti-contamination coatings, has been conducted and the key issues in the use of these coatings highlighted. A summary of the variations in major experiments, including laboratory, wind tunnel and flight testing, is outlined. The effects of surface and material characteristics on insect residue adhesion were also investigated, with topographical features of the surface and surface chemistry shown as influential factors. The use of a substitute as an alternative to live insect testing has shown promise.

Contents

* Corresponding author at: Department of Mechanical, Aeronautical and Biomedical Engineering, University of Limerick, Ireland.
E-mail address: Trevor.Young@ul.ie (T.M. Young).

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1. Introduction

Increasing fuel prices coupled with environmental considerations has led to renewed interest in laminar flow technologies for next generation aircraft. Laminar flow technologies can significantly reduce the drag on aircraft, leading to an increase in airframe aerodynamic efficiency and reduction in fuel consumption, most notably over a long cruise range. A number of studies conducted by aircraft manufacturers, universities, and research institutions – including both large scale wind tunnel and flight tests – have shown the feasibility of these technologies [1–5] that include: Natural Laminar Flow (NLF), Laminar Flow Control (LFC) and Hybrid Laminar Flow Control (HLFC). The use of these concepts is, however, dependent upon the application, as the benefits depend on aircraft size, speed, and wing sweep angle. An in-depth treatise of LFC has been discussed by Braslow [6] and Joslin [7,8].

Briefly, NLF relies on the optimisation of pressure gradients and hence is dependent on the shape of the airfoil. LFC utilises a full-chord suction concept, whereas HLFC is a combination of NLF and LFC (airfoil shape and suction). One overarching requirement that is vital for the utilisation of laminar flow concepts is ensuring a high surface quality. The manufacture and maintenance of smooth wing surfaces is imperative, and several surface requirements have to be considered, namely: (1) the avoidance of any three dimensional disturbances (i.e. rivet heads, insect debris, ice accretion or dust particles); (2) minimisation of surface waviness, either from manufacturing or deformation under cruise loads [9–12]; (3) surface roughness due to the manufacturing process or in-service erosion; and (4) gaps or steps. Deviations in surface smoothness can lead to premature transition of the boundary layer if their size exceeds a critical threshold height. This critical height and the criteria for the onset of transition is variable and dependent on factors including the chordwise position of the disturbance, airfoil profile, angle of attack (AOA) and Reynolds number [6,7,13] – some of these issues are discussed in more detail in Section 2. Many of the above mentioned issues can be addressed during design and manufacture of the structure and proper choice of materials. However, environmental contaminants, insect impact residues in particular, are operational events occurring during the ground operation, take-off, and landing phases of the flight profile. This issue was recognised as early as 1945 by Smith and Higton [12]. Since then, the insect impact residue problem has been a subject of interest, not only as it applies to laminar flow technology for aviation but for the wind farm industry as well, where the influence of such surface irregularities on the aerodynamic efficiency of wind turbine blades and the resulting power losses have also been studied [14].

An early report by Coleman provides a comprehensive review of the insect issue with regards to laminar flow – both implementation issues and mitigation methods – based on what was known at the time it was written [15]. A subsequent report in 1998 by Joslin provided an review of the topic and mitigation concepts investigated [7,8]. Their findings are briefly discussed in this review. Sections 2–4 of this paper describe the aerodynamic, meteorological and entomological factors affecting the accumulation of insect impact residue contamination on aircraft wing surfaces. Section 5 considers the effect of natural cleaning (i.e. flying through clouds, an ice crystal environment or the effect of shear flow) on the extent of the insect residue contamination removal. Section 6 investigates the effect of surface and material characteristics on insect residue adhesion, and identifies limitations in the current knowledge in the area. A description of the different types of anti-contamination measures is briefly discussed in Section 7 with emphasis placed on coatings. Laboratory scale and full wind tunnel and flight testing studies are also described, with notations on variations in the results from each type of test. Section 8 discusses the experimental test methods and procedures that have been developed to test insect contamination, as well as problems associated with testing with live insects. Section 9 examines the dynamics of the insect impact event. The limitations of the use of coatings for aircraft application, especially at the leading edge, are discussed and overall conclusions drawn in Sections 10 and 11.

The most recent efforts discussed within the context of this review were conducted under the European research project AEROdynamic surfaces by advanced MUltifunctional COatings (AEROMUCO) [16,17] which focused on the mitigation of insect debris adhering to aircraft leading edges (wing, empennage, nacelle) using coatings. A comparable and concurrent U.S. investigation conducted under NASA's Environmentally Responsible Aviation Program (ERA) [18] is also discussed herein.

2. Aerodynamic factors affecting insect accumulation

2.1. Critical height to transition

Determination of the critical height (h_{crit}) of a three-dimensional roughness element (e.g. ice, insect debris) required to cause transition of a laminar boundary layer has been investigated by numerous experimentalists. An actual value for the h_{crit} is difficult to specify since it is variable and dependent on a range of factors, including airfoil type and AOA, the flow velocity and freestream turbulence, Reynolds number, the stability condition of the boundary layer, and the streamwise location of the disturbance [7,19–24]. If a disturbance occurs in the laminar flow region of the surface, it can create a wedge-shaped area of turbulent flow, aft of the disturbance (Fig. 1) [25]. These wedge-shapes regions can also form downstream of the impact location, where a small delay in the transition of the boundary layer occurs. For a swept wing, it is particularly important to avoid disturbances near the attachment line as this could adversely affect laminar flow over the entire outboard region of the surface and consequent increase in drag [23,26–28].