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Laboratory testing of insect contamination with application to laminar flow technologies, Part I: Variables affecting insect impact dynamics

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ABSTRACT

The effectiveness of laminar flow technologies can be limited by insect contamination on aircraft leading edge surfaces. In order to effectively manufacture and evaluate anti-contamination coatings a comprehensive understanding of the dynamics of an insect impact event – how the insect ruptures and adheres to the surface – is necessary. Two test facilities (developed independently) were used to study insect impact dynamics; both capable of producing single and multiple insect impacts at speeds of up to 100 m/s. In Part I of this paper, the variables affecting insect impact dynamics are identified. It was found that the effect of angle of impact and impact speed significantly influence the insect residue patterns. Exposure to a constant airflow during the insect impact event imparts a shear force, resulting in an increase in the residue area and a decrease in the height measurements. The dominant factor influencing the rupture velocity (i.e. the lowest speed needed to fracture the exoskeleton) was found to be the orientation of the insect body relative to the surface upon impact. Insect impact dynamics were classed into four separate regimes: sticking, bouncing, spreading and splashing. In Part II of this paper, an evaluation of candidate anti-contamination coatings is presented and the variables affecting the effectiveness of these coatings, such as different insect types and sizes, are assessed.

1. Introduction

The aerospace industry invests significant resources to improve the aerodynamic performance of its commercial aircraft. One method of achieving this is to reduce skin friction drag by employing laminar boundary layers. A number of methods have been developed to increase the laminar region of the boundary layer, including active techniques such as Laminar Flow Control (LFC) and Hybrid Laminar Flow Control (HLFC), which incorporates a forward section of active LFC (usually achieved by suction) and an aft section where the laminar boundary layer is maintained by the airfoil profile alone. These technologies, however, are not without problems, and their susceptibility to surface imperfections and irregularities can potentially degrade the amount of laminar flow achieved [6,10,27]. In recent years, emphasis has been placed on the development of surface coatings that significantly reduce surface irregularities caused by ice accretion, dirt and/or insect adhesion. Experimental methods and procedures to test coatings against ice accretion are well established [28,34,35,37,51,57]; however, at present, no standardised evaluation methods or test equipment are available for testing the adherence of insect debris to aircraft surfaces. Previous test methods used to evaluate the effectiveness of anti-contamination coatings have included flight tests [47,63], wind tunnel tests [10,33,64,65] and road testing [15,53,68]. Custom-built insect delivery devices or "insect guns" have been developed by Lorenzi et al., Smith et al. and Young et al. [39,54,71]. Test procedures that have been adapted to screen and evaluate the adhesion strength of insect haemolymph to anti-contamination coatings are currently used by aircraft manufacturers [21] and research institutions [31]. However, these test methods and are not standardised and it is not known how comparable different test methods are, as different test equipment and laboratory conditions can present significantly different results. This was recently shown by Wohl et al. [63] of NASA Langley – it was noted that a coating that performed well during flight testing was one of the worst performing coatings during the wind tunnel tests. This confirmed previous hypothesis that the adhesion of insect residues is a complex phenomenon not only influenced by material type and surface

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Table 1
Insect mass.

Insect type (Test facility)	Mass (mg)
D. melanogaster (SPIrIT)	0.81 ± 0.14
D. melanogaster (iCORE)	1.19 ± 0.03

characteristics but also aerodynamic factors (e.g. aircraft wing geometry and velocity), entomological factors (e.g. species of insect encountered and insect density) and environmental factors (e.g. rain) [10].

Insect density is highest for ambient temperature and wind speed of approximately 25 °C and 2.5–5 m/s respectively [10,20,46]. The accumulation of insects on aircraft occurs predominantly at altitudes below 150 m [42,68], corresponding to taxi, take-off and landing and low level climb and descent. The effect of insect debris on the aerodynamic efficiency of the aircraft is critical during the cruise segment of the flight, particularly for long haul sectors, as analysed by Young [69,70]. The insect debris adheres to the aircraft surface through activated components in the insect haemolymph. When an insect's body ruptures upon impact, a process similar to that of wound healing occurs. Inactive proenzymes, such as phenoloxidases (POs), are synthesised by hemocyte cells and become activated. This causes an increase in the viscosity of the fluid, and coupled with the coagulation of the haemolymph, binds the crushed exoskeleton to the surface [41,50,55,56,58]. If the debris exceeds a critical height, h_{crit}, transition of the boundary layer occurs, leading to a localised region of turbulent boundary layer and a corresponding increase in skin friction drag. If this occurs at numerous locations, it will significantly increase the fuel consumption and the benefits of laminar flow will not be realised. The critical height is dependent on a range of factors including the chordwise position of the impact, airfoil profile and Reynolds number [4,10,22,26,27,40].

In recent years, the University of Limerick has developed a number of insect impact tests facilities, namely SPIrIT (Stationary samPle Insect Impact Test), for the evaluation of anti-contamination coatings as part of the FP7 project AEROMUCO (AEROdynamic surfaces by advanced MUltifunctional COatings) [31,71]. Independently, EADS IW (Ottobrunn, Munich) established iCORE (Icing and Contamination Research Facility) to test the susceptibility of aircraft wing coatings to ice accretion and/or adhesion and insect contamination [16]. Part I of this paper gives an overview of both test facilities and aims to identify the key factors influencing insect impact dynamics, in particular the rupture velocity (i.e. the speed needed to fracture the exoskeleton), impact velocity and impact angle. Challenges in testing with live insects are also identified. Part II of this paper focuses on the evaluation of a range of anti-contamination coatings and different variables affecting the effectiveness of these coatings, including insects of different types and sizes.

2. Experimental materials and methods

2.1. Insects

Wild-type (WT) *Drosophila Melanogaster* (hereafter referred to as *D. melanogaster*) were purchased from a local hardware store and weighed on an Explorer® Analytical Balance with a resolution of 1×10^{-6} g. For each measurement a minimum of three replicates were used (Table 1). *D. melanogaster* is frequently used for insect contamination testing, as the insect species and size represents those with the highest incidence rates during flight [14,17,23]. Differences in mass of *D. melanogaster* used during testing could be attributed to a difference in diet and growth environment [11,12].

2.2. Materials

Aluminium alloy (AA2024-T3 clad) was used as a reference material (Specimen 1). AA2024-T3 clad is a typical material used on major commercial aircraft for protection against erosion on wing leading edge surfaces. The material was also used as a substrate and was pre-treated by Cr (VI) free anodising and coated with a primer, a basecoat and a conventional 3K polyurethane clear-coat (Specimen 2). The anodising process based on Cr (VI) compounds is widely used as it provides excellent corrosion protection [5,18]. Polyurethanes are commonly used for topcoats in aerospace coating systems, and are typically used on external surfaces of the aircraft (e.g. fuselage, wings and stabilisers) [8,13].

2.3. Insect residue analysis

2.3.1. Area and height analysis

Insect residue area analysis was conducted using images taken with a Fujifilm FinePix S8000FD camera and processed using image analysis software ImageJ. Insect residue heights were measured using a Zeiss LSM710 Confocal Laser Scanning Microscope (CLSM) with an objective of 20×. Results were averaged from a minimum of ten impacts ($n = 10$) per coating type.

2.3.2. Topography

The topography of the insect residues was examined using a Hitachi SU-70 field-emission Scanning Electron Microscope (SEM). An ultra-thin layer of electrically-conducting material (gold) was deposited on the specimens prior to imaging. Microscopic images were taken using a Zeiss Optical Microscope AXIO Imager A1 at magnifications ranging from ×5 to ×20.

2.4. Test facilities

2.4.1. Stationary samPle insect impact test SPIrIT (University of Limerick)

The SPIrIT (Stationary samPle Insect Impact Test) facility uses compressed air to accelerate the insect, which is placed in a sabot (or cartridge). The system consists of a compressed air tank, which can be pressurised to a maximum value of 520 kPa. The firing mechanism incorporates a solenoid-operated diaphragm valve. The switch used to activate the solenoid can also be used to trigger a high speed camera. The sabot, made of compressible foam, is accelerated down a smooth bore tube when the diaphragm valve is opened. The sabot has a multifunctional job: it provides a method to accelerate the insect(s) to high velocities, while keeping the insect(s) intact during the high initial acceleration. To prevent the sabot from hitting the stationary test specimen and interfering with the impacted insect(s), the tube decreases in diameter causing the sabot to decelerate, before it comes to a complete stop at the end of the tube. The excess air pressure is then released through an exhaust positioned just behind the stopped sabot (Fig. 1). The test speed is measured using a Photron® SA1.1 high speed camera (camera position 1). The SPIrIT can operate at low speeds (10 m/s) but is designed to operate at much higher speeds (ca. 100 m/s). The insect impact velocity can be controlled by a combination of chamber pressure and increasing the distance between the exit of the tube and the test specimen. The distance travelled by the insect, once leaving the sabot, before hitting the target is relatively short and the insect trajectory is nearly straight and observed to be consistent.

2.4.2. Insect impact test procedure for SPIrIT (University of Limerick)

Anti-contamination coatings were cut to size and attached to the target area. Insects were temporarily immobilised using CO_2 before inserting them into the sabot. The sabot was then placed