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Tomographic particle image velocimetry of desert locust wakes: instantaneous volumes combine to reveal hidden vortex elements and rapid wake deformation

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Aerodynamic structures generated by animals in flight are unstable and complex. Recent progress in quantitative flow visualization has advanced our understanding of animal aerodynamics, but measurements have hitherto been limited to flow velocities at a plane through the wake. We applied an emergent, high-speed, volumetric fluid imaging technique (tomographic particle image velocimetry) to examine segments of the wake of desert locusts, capturing fully three-dimensional instantaneous flow fields. We used those flow fields to characterize the aerodynamic footprint in unprecedented detail and revealed previously unseen wake elements that would have gone undetected by two-dimensional or stereo-imaging technology. Vortex iso-surface topographies show the spatio-temporal signature of aerodynamic force generation manifest in the wake of locusts, and expose the extent to which animal wakes can deform, potentially leading to unreliable calculations of lift and thrust when using conventional diagnostic methods. We discuss implications for experimental design and analysis as volumetric flow imaging becomes more widespread.

Keywords: biomechanics; biomimetics; locust; aerodynamics; Particle Image Velocimetry; flight

1. INTRODUCTION

Our knowledge of how animals move through fluids has long been reliant upon theoretical work with experimental studies using animals trailing behind owing to the challenging proposition of directly observing fluid flows that are small in scale and highly time dependent [1]. This is particularly important in the realms of insect flight where those difficulties are at their most severe. The most established flow diagnostic technique for animals moving through fluids is particle image velocimetry (PIV). Recent increases in the power of financially viable lasers have contributed to an acceleration in our descriptive and quantitative understanding of the flows induced by flying animals and thereby the mechanics of their locomotion. Despite this major step forward in our capacity to measure the flows induced by beating wings, single-camera PIV and twin-camera stereo-PIV techniques that have been used to date yield either two-component or three-component vectors arranged on a two-dimensional plane through the animal's wake (2D-2C, or 2D-3C). A particle-tracking technique has successfully been used to capture measurement volumes in water and applied to the hydrodynamics of fish swimming [2,3] but reconstructions of the three-dimensional wake structure of animals flying in air necessarily rely on the post hoc reconstruction of a pseudo-volume by stacking transverse (i.e. normal to the wind or water tunnel freestream) flow field planes that have not been captured simultaneously. If the ratio of wind tunnel speed to sampling frequency is very small, then plane-stacking may be reasonable because the displacement between successive imaging events is small and, between them, the wake will have had little time in which to deform. We can, therefore, be reasonably confident that the pseudo-volumetric data given by a stack generated under those conditions is a realistic representation of the animal's wake. Sophisticated advection-based modelling has proved somewhat successful in artificially increasing the sampling rate of PIV data [4], but as wind tunnel speed increases, or if sampling frequency is relatively low, then the planes to be stacked become

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