Vortex Dynamics of Flapping Insects in Fully Developed Turbulence

Thomas Engels[1,2,⋆], Dmitry Kolomenskiy[3], Kai Schneider[4], Marie Farge[2], Fritz-Olaf Lehmann[5] and Jörn Sesterhenn[1]

[1] ISTA, Technische Universität Berlin, Müller-Breslau-Strasse 12, 10623 Berlin, Germany

[2] LMD-CNRS, École Normale Supérieure and PSL, 24 rue Lhomond, 75231 Paris Cedex 05, France

[3]Biomechanical Engineering Laboratory, Chiba University, 1-33 Yayoi-Cho, Inage-Ku, Chiba-Shi, Chiba, 263-8522 Japan

[4]I2M-CNRS, Aix-Marseille Université, 39 rue Joliot-Curie, 13451 Marseille Cedex 20 France

[5]Department of Animal Physiology, Universität Rostock, Albert-Einstein-Str. 3, 18059 Rostock, Germany

⋆ corresponding author: thomas.engels@mailbox.tu-berlin.de

Insect flight currently receives considerable attention from an interdisciplinary community of researchers. This growing interest is fostered by the recent trend in miniaturization of unmanned aerial robots that naturally incites reconsidering flapping flight as a bioinspired alternative to conventional airplane design. For all flyers it is challenging to fly outdoors in a turbulent environment, and it is important to learn how insects face that challenge.

Among the variety of flying insects we choose bumblebees as prototype for a medium-sized flyer with a Reynolds number of around 2000. This choice is motivated by the available data and the fact that these animals are known to fly even under particularly difficult conditions [1, 5].

Our approach is to use high-resolution direct numerical simulations to obtain a precise description of the flow field generated by the bumblebee. The numerical method is based on a spectral discretization in combination with the volume penalization method [4]. The fluid is described by the incompressible Navier–Stokes equation and all fluid scales are resolved. A total of 680 million grid points is used.

Contrarily to experiments, numerical simulations allow to impose a well known turbulent perturbation upstream of the model insect, while keeping the wingbeat unaltered. Real animals adapt their wingbeat to the perturbations, and measuring the flow field as well as the kinematics simultaneously is challenging as many insects avoid flying in smoke, as would be required for PIV measurements, for instance.

Our bumblebee model and the flow it generates is visualized in Fig. 1. In this figure, the inflow condition is laminar. The insect is fixed in the virtual wind tunnel, i.e., tethered flight is considered. In a first part, we focus on this flow field in order to get a landmark for what turbulence is relevant to the insect at its particular scales. To this end, we study the role of helicity $h = \underline{u} \cdot \underline{\omega}$ generated by the wings, which is, amongst others, a measure for the depletion of non-linearity in the Navier–Stokes equations. Helicity is, therefore, an important quantity to describe coherent structures. We show that the leading edge vortex, which is the most important vortical structure in flapping flight, is strongly helical [2] and further employ an orthogonal wavelet decomposition to show at what scales the helicity is generated. This analysis is also performed for the simplified setup of a single bumblebee wing which is revolving around a fixed axis at fixed angle of attack.

After analyzing the laminar inflow case, we proceed to studying the model insect in turbulent inflow. The laminar case revealed a turbulence intensity $Tu = u'_{\mathrm{RMS}}/u_\infty$ of about 20% in the wake of the bumblebee, which would be the magnitude of perturbations a bumblebee flying behind another one, for example at the nest entrance. We vary the Reynolds number of the superimposed turbulent perturbations, which are obtained by simulations of homogeneous isotropic turbulence [3], yielding turbulence intensities Tu between 16% and 100%, thus from mildly to highly turbulent. This model turbulence is well established, and as all wake turbulence eventually becomes isotropic it is considered a realistic description of field-relevant turbulence. We find that the leading edge vortex is stable under turbulent conditions and that the model produces, when ensemble-averaged, the same force as under laminar inflow condition, at the same power

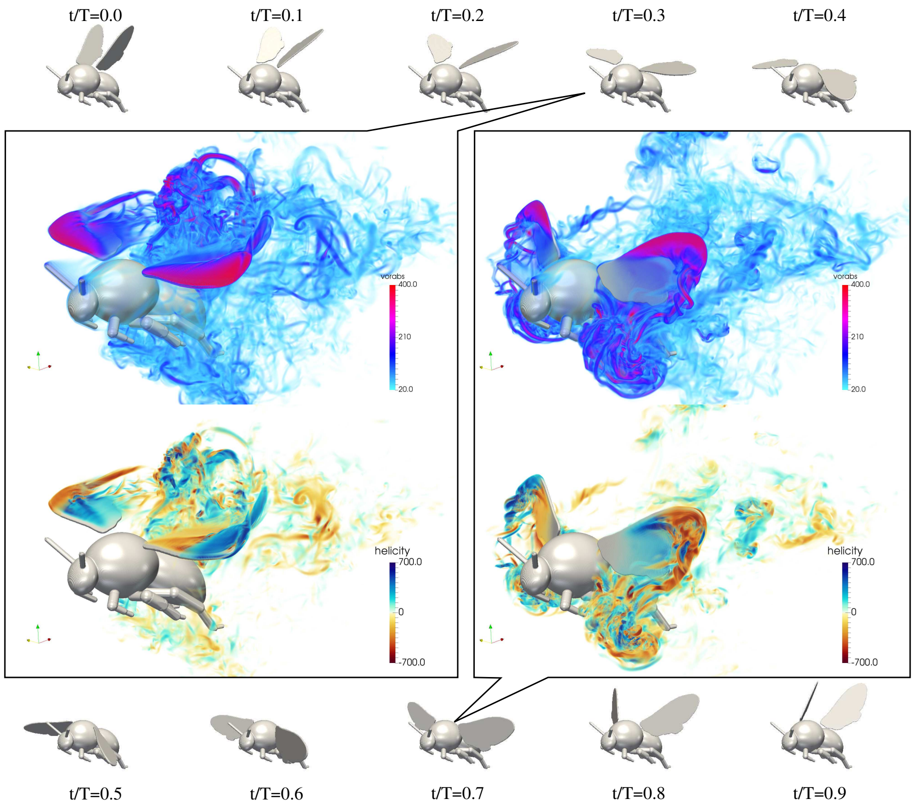

Figure 1: Model bumblebee used in the present work. Top/ bottom row visualize the prescribed wingbeat for the up/downstroke. Center figures visualize the flow field by volume rendering of vorticity and helicity for two time instants during up- and downstroke. T is the period time.

consumption. We also investigate the impact of the turbulence-induced fluctuations in forces and moments on the flight stability of the model.

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