Helical vortices generated by flapping wings of bumblebees

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

[1] *M2P2-CNRS, Aix-Marseille Université, Marseille, France*
[2] *ISTA, Technische Universität Berlin, Berlin, Germany*
[3] *Biomechanical Engineering Laboratory, Chiba University, Chiba, Japan*
[4] *LMD-CNRS, Ecole Normale Supérieure, Paris, France*
[5] *Department of Animal Physiology, Universität Rostock, Rostock, Germany*

Summary

Insects fly even under heavy turbulent air flow conditions. To understand the impact of turbulent fluctuations on the aerodynamics of flapping wings, we model a bumblebee with fixed body and prescribed wing motion, flying in a numerical wind tunnel. The inflow condition of the tunnel varies from unperturbed laminar to strongly turbulent. Massively parallel simulations show that turbulence does not significantly alter the wing's leading edge vortex that is required for elevated lift production. Mean flight forces, moments and aerodynamic power expenditures are thus unaffected, suggesting little significance of turbulence on overall flight performance in insects. The increase in variance of the aerodynamic measures with increasing turbulence intensity, however, leads to flight instabilities in freely flying animals. Here we focus on analyzing the helicity of the generated vortices and study their contribution at different scales using wavelets.

Insect flight receives considerable attention from both engineers and biologists. This growing interest is fostered by the recent trend in miniaturization of unmanned air vehicles that naturally incites reconsidering flapping flight as a bio-inspired alternative to fixed-wing and rotary flight. For all small flyers it is challenging to fly outdoors in an unsteady environment, and it is essential to know how insects face that challenge.

Current research on the flow generated by flapping wings indicated the important role of the leading edge vortex. This vortex has a conical structure to due the three-dimensional motion of the wings. This flow configuration produces strong vorticity on the sharp leading edge and the outwards velocity (from the root to the tip of the wing) in the span-wise direction, see e.g. [4, 5]. Such flows are characterised by strong helicity, see fig. 1.

The aim of the present work is to analyze high resolution numerical simulation data of a bumblebee flying in turbulent flow, presented in [1]. We focus on the helicity of the generated vortices and use the orthogonal wavelet decomposition to analyze the scale dependence of helicity.

The bumblebee flaps its wings at Reynolds numbers of approximately 2000 at forward flight speed of 2.5 m/s. We developed a numerical wind tunnel and placed the animal in a $6R \times 4R \times 4R$ large, virtual rectangular box, where $R = 13.2$ mm is the wing length. The computational domain is discretized with 680 million grid points and the three-dimensional Navier-Stokes equations are solved by direct numerical simulation on a massively parallel computer. The volume penalization method is used to handle the no-slip boundary conditions on the time-varying geometry. The mean inflow velocity accounts for the equivalent forward flight speed of the tethered insect. For simplicity we modeled the wings as flat rigid plates with prescribed kinematics. To model atmospheric turbulence, we used homogeneous isotropic turbulence (HIT) as turbulent inflow. We varied the turbulence intensity by altering the energy content of the turbulent perturbations superimposed to the mean flow. The entire procedure allowed us to study insect flight from laminar to fully-developped turbulent flow conditions. Details on the numerical code, which is open source, can be found in [2].

A visualization of the flow fields of the bumblebee with laminar inflow is shown in fig. 1. The isosurfaces of the Q-criterion illustrate the vortical structures generated by the flapping wings. To get insight into the helicity of the vortices we colored the isosurfaces with the relative helicity,

$h(\boldsymbol{x}) = \frac{\boldsymbol{u}\cdot\boldsymbol{\omega}}{|\boldsymbol{u}|\,|\boldsymbol{\omega}|}$, where $\boldsymbol{u}$ is the velocity field and $\boldsymbol{\omega} = \nabla \times \boldsymbol{u}$ the vorticity field. Values of ± 1 correspond to alignement and anti-alignement of vorticity with velocity vectors, respectively. Integrating the helicity over the half-space of the computational domain with respect to the vertical centerplane of the insect, one obtains the mean helicity generated by the left and the right wing. The time evolution of both contributions is shown in fig. 2 for laminar and turbulent inflow. We observe that the left and right wing contributions behave similarly with opposite sign and that in the turbulent case the amplitudes are much larger. Decomposing the velocity and vorticity fields into orthogonal wavelets the scale-dependent helicity can be introduced. For a review we refer to [3]. We note that it preserves Galilean invariance, though the kinetic helicity itself does not. In the talk we shall present analyses of the generated vortices using scale-dependent helicity to examine at which scales the alignment is most pronounced. The challenging question, how the turbulent inflow modifies the scale distribution, will thus be clarified.

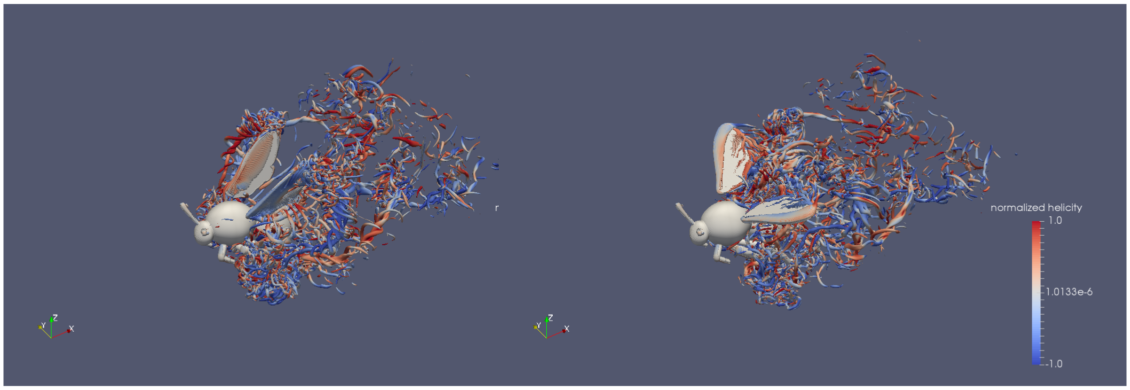

Fig. 1: Bumblebee in laminar inflow: Isosurfaces of Q-criterion colored with relative helicity h.

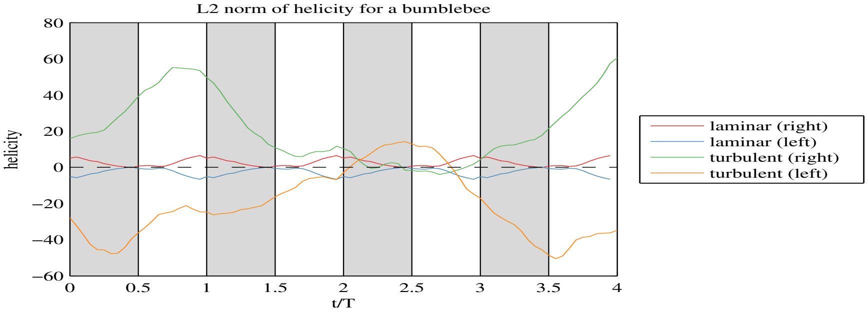

Fig. 2: Time evolution of the helicity H integrated over the left and right domain with respect to the vertical center plane of the bumblebee for laminar inflow and turbulent inflow.

References

[1] T. Engels, D. Kolomenskiy, K. Schneider, F.O. Lehmann and J. Sesterhenn. Bumblebee flight in heavy turbulence. *Phys. Rev. Lett.*, 12/2015, accepted.

[2] T. Engels, D. Kolomenskiy, K. Schneider and J. Sesterhenn. FluSI: A novel parallel simulation tool for flapping insect flight using a Fourier method with volume penalization. arXiv:1506.06513, 2015.

[3] M. Farge and K. Schneider. Wavelet transforms and their applications to MHD and plasma turbulence: a review. *J. Plasma Phys.*, **81**(6), 435810602, 2015, arXiv:1508:05650.

[4] D. Kolomenskiy, H.K. Moffatt, M. Farge and K. Schneider. Two- and three-dimensional numerical simulations of the clap-fling-sweep of hovering insects. *J. Fluids Struct.*, *27*, 784-791, 2011.

[5] D. Kolomenskiy, Y. Elimelech and K. Schneider. Leading-edge vortex shedding from rotating wings. *Fluid Dyn. Res.*, **46**, 031421, 2014.