On flapping flight in turbulence

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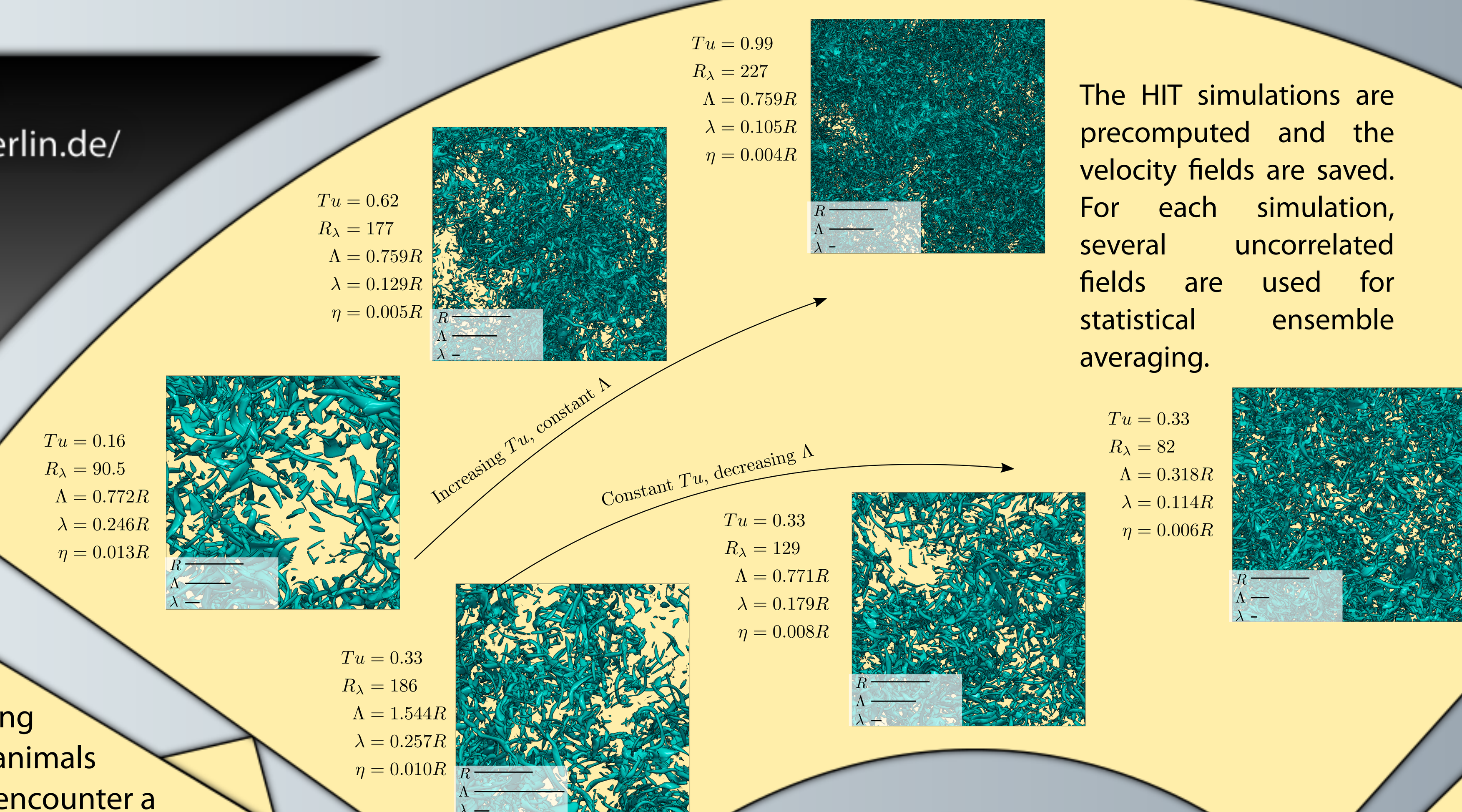
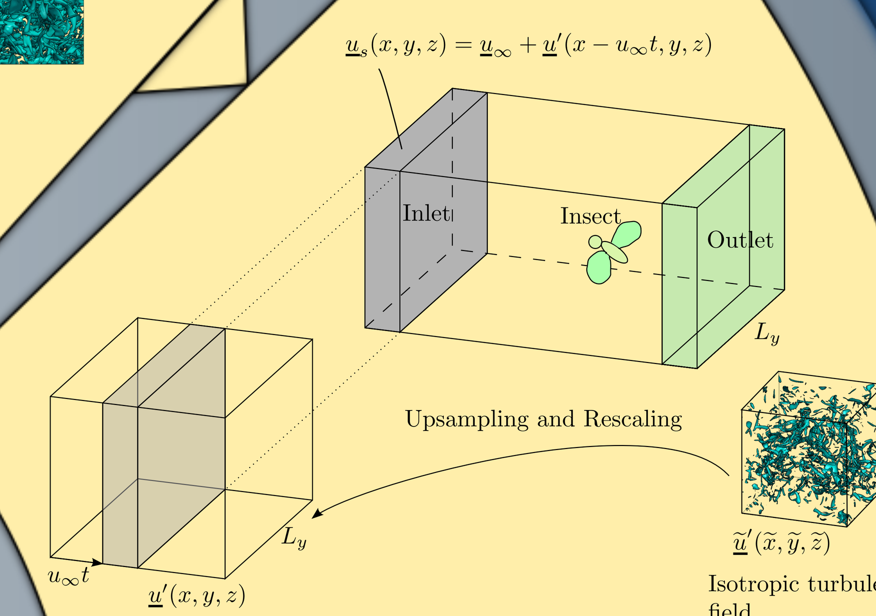
Model Turbulence

When flying outdoors, animals and robots encounter a large range of turbulent aerial perturbations, e.g. atmospheric and bluff-body turbulence, which depends on a large number of parameters. To reduce the parameter space, we use homogeneous isotropic turbulence as model for inflow turbulence, described by the energy, integral scale and Reynolds number.



The HIT simulations are precomputed and the velocity fields are saved. For each simulation, several uncorrelated fields are used for statistical ensemble averaging.

Dynamic scaling:
$$\underline{u}' = \frac{2\pi\nu}{L_y\tilde{\nu}}\tilde{\underline{u}}'$$



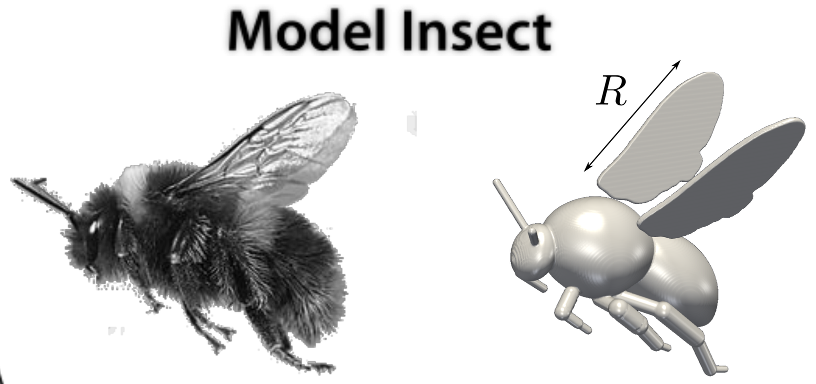
Motivation

Recent trends in miniaturization have fostered the interest in insect flight as bio-inspired alternative to conventional fixed-wing or rotary flight. When flying outdoors, animals and robots encounter a large range of turbulent aerial perturbations, e.g. atmospheric and bluff-body turbulence (e.g. from flowers). We currently know very little about how insects manage to fly on a windy day. In this study we use homogeneous isotropic turbulence as generic model turbulence and couple it to a state of the art insect flight solver, allowing us to investigate the problem from the numerical point of view.

Our main questions are:

1) How does turbulence affect flapping flyers?
2) Which scales of turbulent motion are most relevant?
3) an turbulence destroy the leading edge vortex?

Model Insect

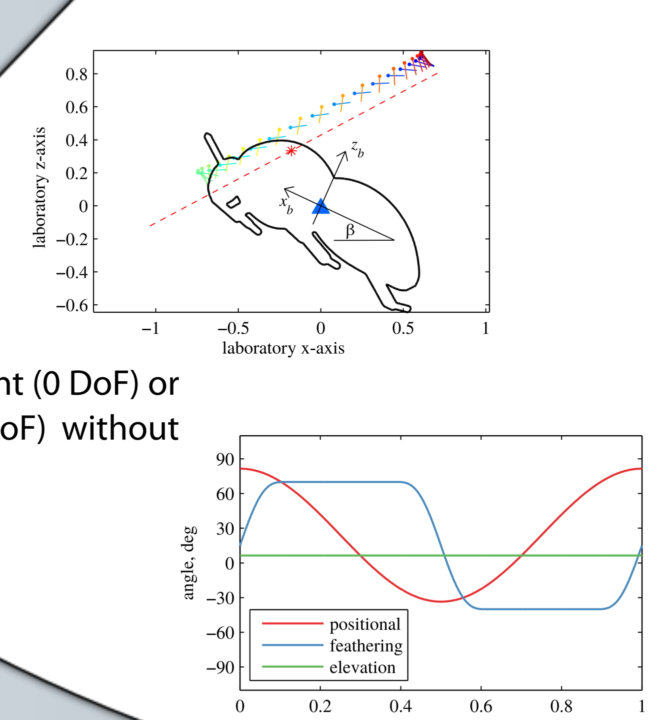


Among the flying insects, we choose the bumblebee known to forage in difficult weather and large enough for a variety of scales.

key parameters:

$R = 13.2\,\mathrm{mm}$
$f = 152\,\mathrm{Hz}$
$u_\infty = 2.5\,\mathrm{m/s}$
$m = 175\,\mathrm{mg}$
$Re = 2060$

Wingbeat kinematics are described in [1].



Either fixed flight (0 DoF) or free-flight (6 DoF) without control

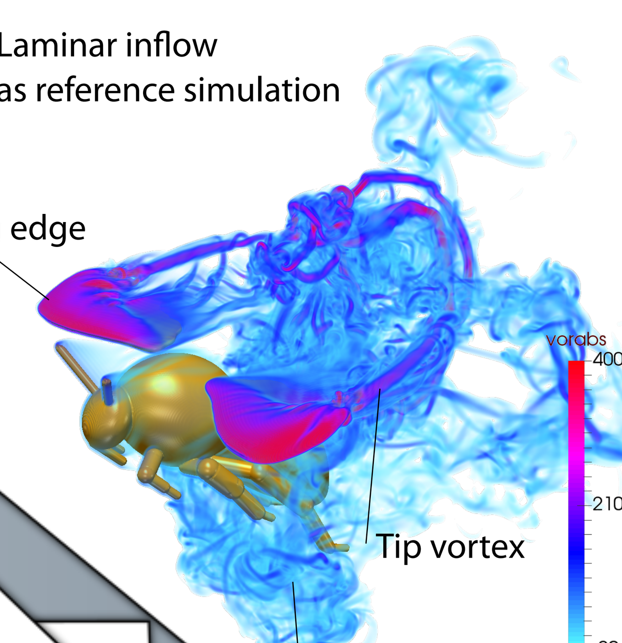
The numerical method is based on the volume penalization method and a Fourier discretization. All scales are resolved on a fine grid. The FluSI code is open-source and freely vailable. All computations are done on massively parallel machines. Details can be found in [2].

FluSI code

$$\partial_t \underline{u} + \underline{\omega} \times \underline{u} = -\nabla\Pi + \nu\nabla^2\underline{u} - \frac{\chi}{C_\eta}\left(\underline{u} - \underline{u}_s\right)$$

$$\nabla \cdot \underline{u} = 0$$

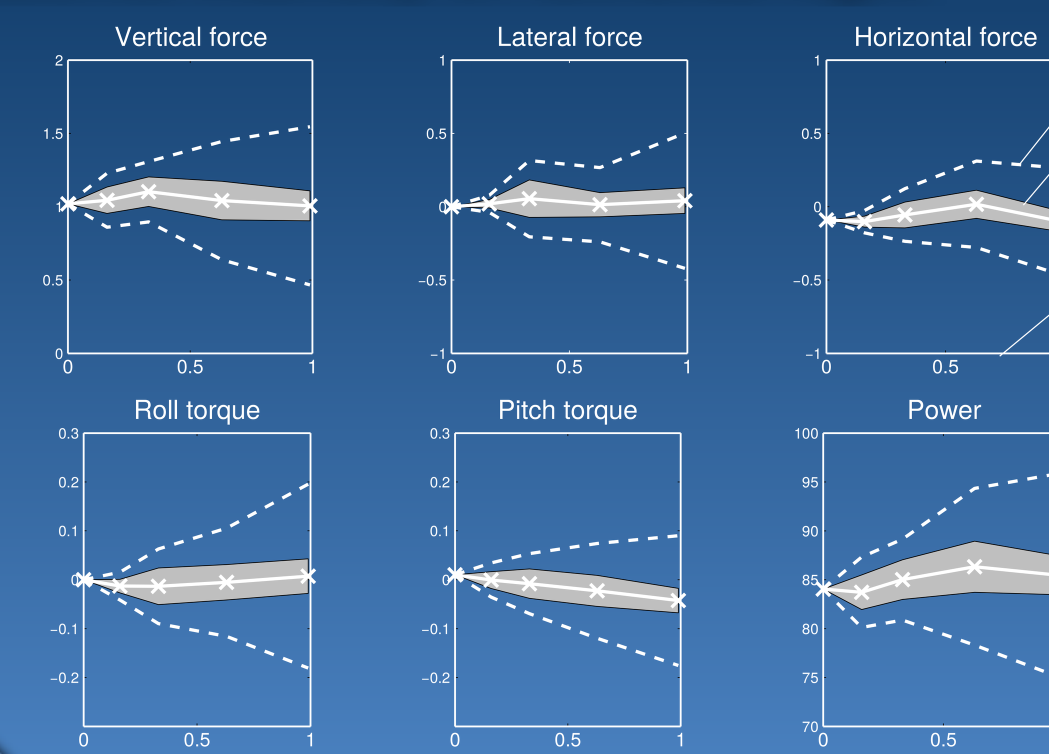
Penalization term



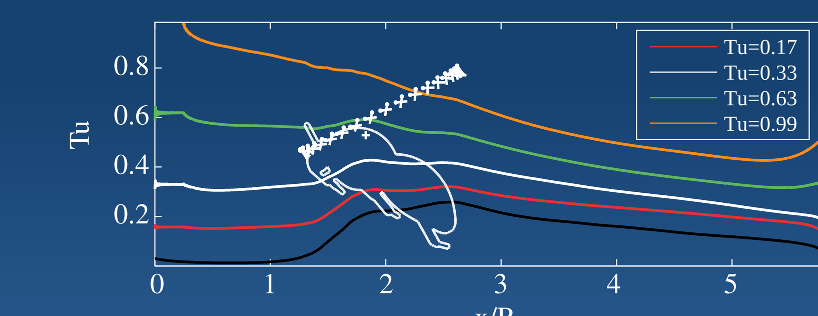
Results

Influence of turbulence intensity on tethered flight

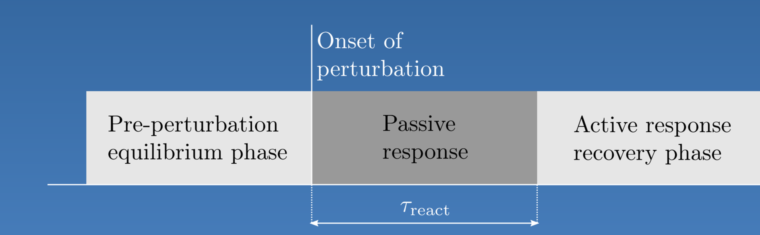
First we study the influence of turbulence intensity [1] on a thethered insect. Based on the wake turbulence generated by the insect itself we choose intensities between 16% and 99%, which contains the experimental range from [3].



Even in strongest turbulence, the ensemble averages remain constant, but fluctuations occur. On average, the leading egde vortex remains intact. Turbulence is a problem for control, rather than for force production.

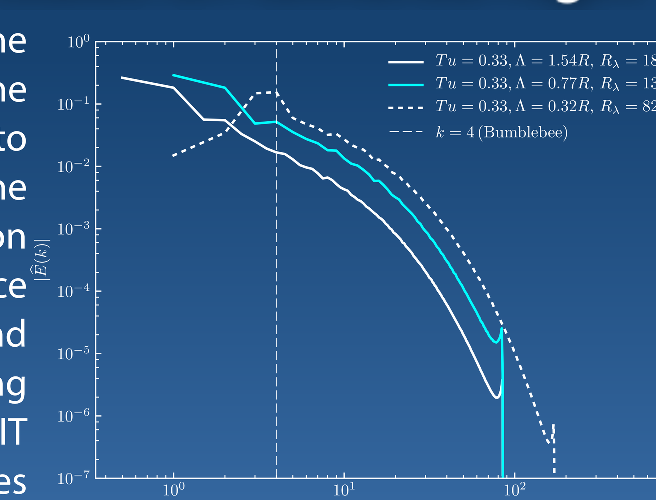


Slab averaged turbulence intensity as a function of the axial coordinate, with the insect drawn to scale for orientation. The black line is the laminar case.



Influence of turbulent scales on tethered flight

In the next step, we define different turbulence fields for the same turbulence intensity, to study what influence the different length scales have on the flyer. The turbulence intensity is fixed to 33% and by varying the forcing wavennumber in the HIT simulation, but the scales are altered.



The fluctuations in forces and moments are very sensitive to changes in the integral length scale. If it is smaller than the wing length, fluctuations decrease significantly, while the changes between 0.77 R and 1.54 R are smaller.

We conclude that it is rather the scale dependent energy which matters for the insect than simply the turbulent kinetic energy.

Tu	Case	Force x	Force y	Force z	Moment x	Moment y	Moment z	Power
0.0	laminar	-0.087	-0.001	1.017	0.000	0.009	0.000	83.993
0.33	coarser	-0.001	0.018	1.063	0.010	0.040	-0.020	83.267
0.33	PRL/air	-0.057	0.055	1.106	-0.013	-0.009	0.037	84.844
0.33	f ner	-0.077	0.001	1.015	-0.001	0.003	0.010	82.735

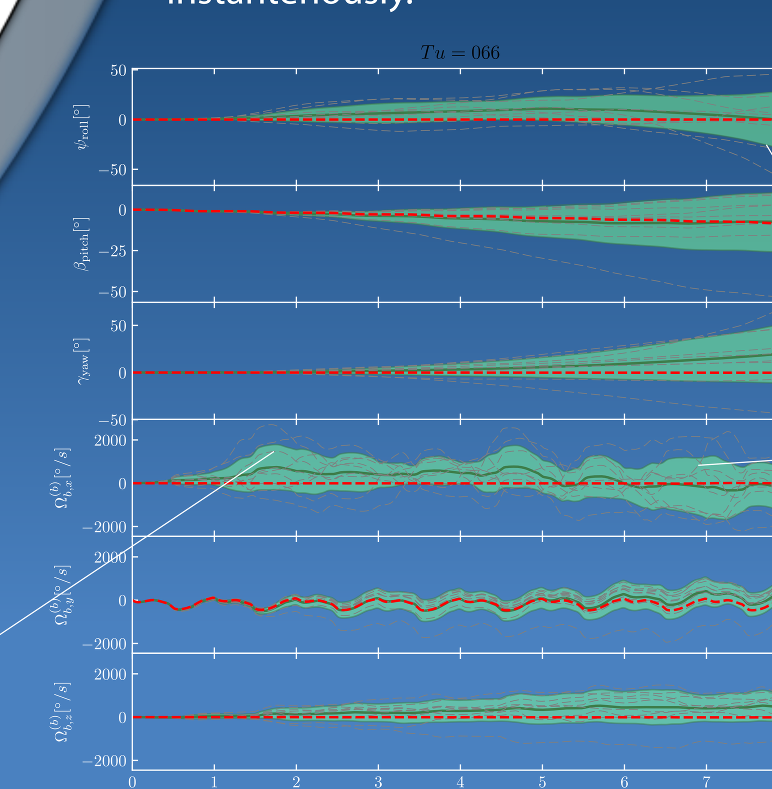
Table 1: Full-cycle and ensemble averaged data for forces, moments (roll, pitch, yaw) and power.

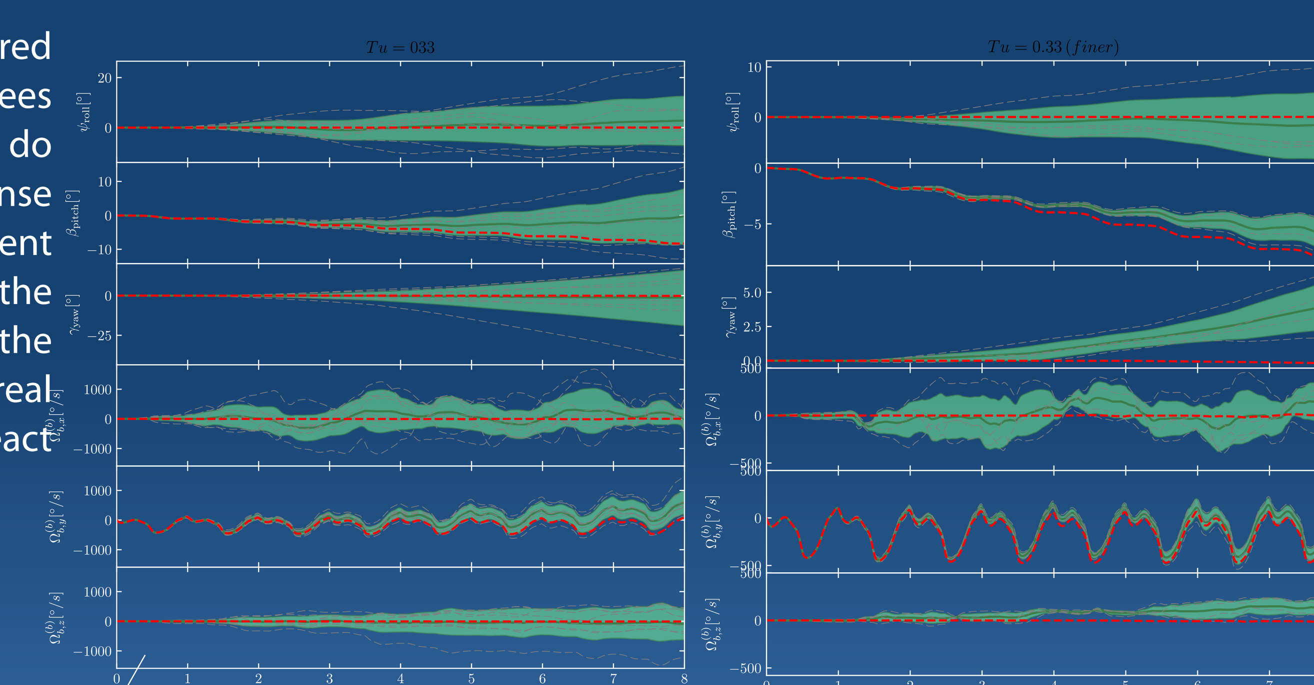
Tu	Case	Force x	Force y	Force z	Moment x	Moment y	Moment z	Power
0.0	laminar	-	-	-	-	-	-	-
0.33	$\Lambda = 1.5$	0.176	0.109	0.148	0.104	0.095	0.076	3.739
0.33	$\Lambda = 0.77$	0.179	0.260	0.206	0.076	0.061	0.049	4.073
0.33	$\Lambda = 0.32$	0.050	0.050	0.086	0.035	0.027	0.023	1.795

Table 2: Standard deviations σ of the full-cycle averaged data for forces, moments (roll, pitch, yaw) and power.

Free-flight in turbulence (6 DoF, ongoing work)

We previously considered tethered flight and now release all 6 degrees of freedom. As our simulations do not incorporate control, the response of the system to the turbulent perturbations are relevant during the reaction time interval, which is the delay in wingbeat adaption in real insects, as they cannot react instantenously.



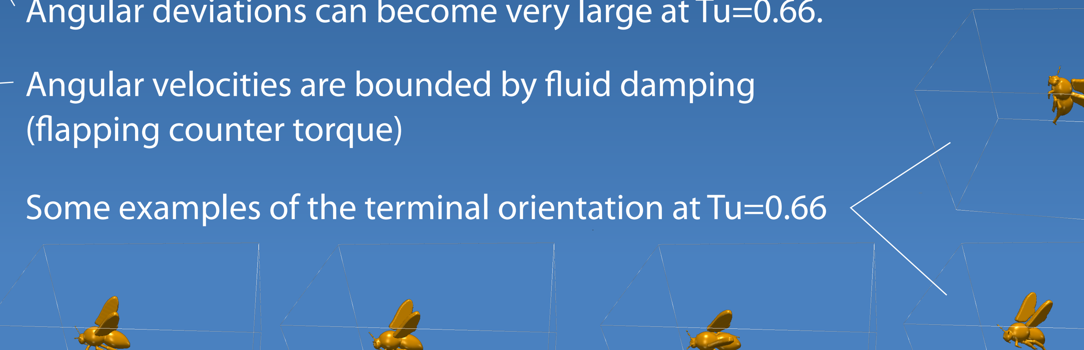


The influence of turbulent scales (left: 0.77R, right: 0.32R) is confirmed in the free-flight case, as the deviations form the laminar case are much smaller.

Angular deviations can become very large at Tu=0.66.

Angular velocities are bounded by fluid damping (flapping counter torque)

Some examples of the terminal orientation at Tu=0.66



The roll direction is the most sensitive

References

[1] T. Engels, D. Kolomenskiy, K. Schneider, F.O. Lehmann and J. Sesterhenn. *Bumblebee flight in heavy turbulence*. Phys. Rev. Lett., 116, 028103, 2016.
[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*. SIAM J. Sci. Comp., 38(5), S03-S24, 2016
[3] Crall et al. *Foraging in an unsteady world: bumblebee flight performance in field-realistic turbulence*. Interface 2016