3D flow and deformation measurements of rigid and flexible wings under combined pitching and plunging motions using Lagrangian particle tracking

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Abstract

A dynamic test rig based on a hypocycloid gear (Huhn 2015) has been designed at DLR for underwater flapping wing applications (see Figure 1 a and b). Three NACA0012 wings with different flexibility, to be attached to the end plate, have been constructed (half span: 150 mm, chord: 50 mm). The wings perform a two-dimensional motion, i.e. within the x,z-plane, whereas the pitch axis is constantly pointing in the y-direction. Markers with approx. 0.5mm diameter were printed onto the wings with pseudo-random distribution to allow detection of the wing motion and deformation (see Figure 1 c and d).

The dynamic test rig was installed in the closed-circuit water tunnel at the Aerodynamic Institute (AIA) of the RWTH-Aachen tunnel to investigate the instantaneous aerodynamics of flapping wings (see Figure 1 f and g). The facility provides a 1.5 m wide and 1 m high test section and was operated at a free stream velocity of U = 0.44 m/s. A system of eight high-speed cameras (Phantom v2640, v1840 and T1340) were installed in two groups at both sides of the tunnel, providing a full view around the moving wings (see Figure 1 e and h). Illumination was realized using three high-power LED arrays, collimated by a 1000 mm lens and located beneath the tunnel. By using a passe-partout, a circular light volume with approx. 200 mm diameter was created, which was completely seen by all cameras (apart from the regions blocked by the wing for each camera). The spanwise extent of the measurements volume is approx. 220 mm. The water was seeded using 60 µm polyamide particles from *Orgasol*. The cameras and LEDs were operated at 2kHz repetition rate, yielding sequences of 12597 at the full camera resolution of 4 MPx. Various pitching and plunging motions at a frequency of 1.03 Hz were realized for all three wings, both with and without water flow.

The cameras were calibrated using a 3D calibration target from LaVision, which was translated by 150 mm in lateral direction. Volume-self-calibration (Wieneke 2007) and OTF calibration (Schanz et al. 2013) were applied. Figure 2 a) shows the positions of the cameras as given by the calibration in relation to the common volume, seen from above.

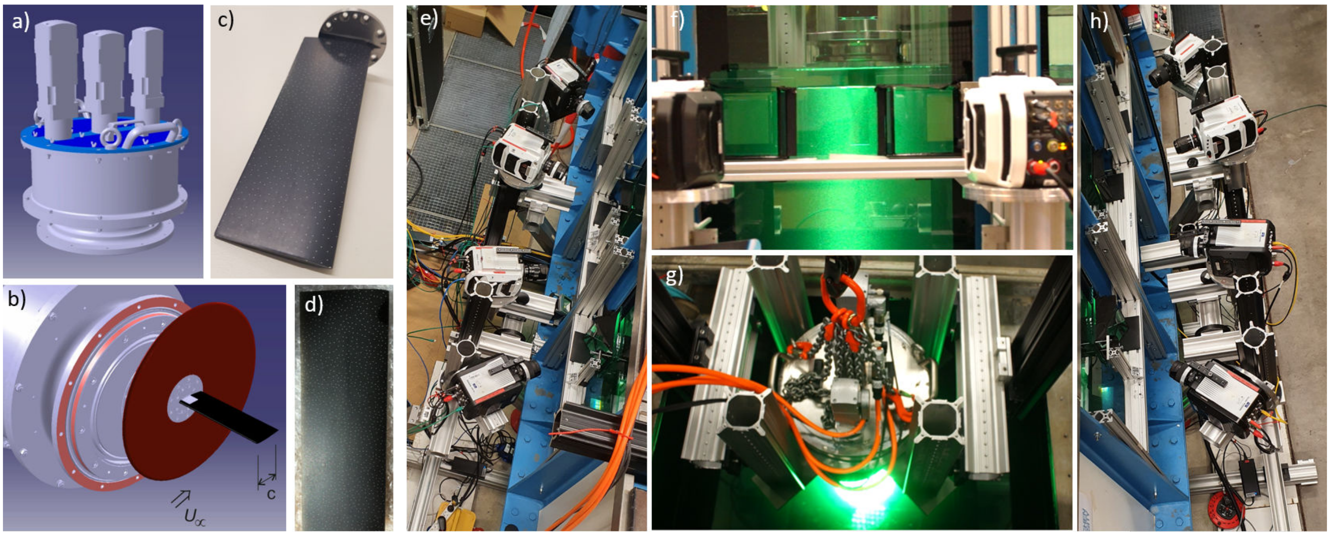

Figure 1: a) DLR dynamic test rig with three synchronized servo motors and gear box; b) half wing installed on end plate; c) rigid wing; d) flexible wing; e) and h) 4 cameras installed on each side of the water tunnel, forming a common camera system; f) side view of illuminated wing and particles; g) dynamic test rig installed on the top of the water tunnel

Both the particles, as well as the markers on the wing have been captured within the same images. The aim is to separately track both kinds of 3D points all around the model via Lagrangian particle tracking using the Shake-The-Box (STB) method (Schanz et al. 2016).

Evaluation starts with the detection of the wing. As a total of six cycles of the wing movement was captured in each run, a separation of the wing markers from the particle images is possible via the minimum images of the captured six instances of each phase. The tracking of the wing markers is then performed using STB on these minimum images, available for one full cycle. Figure 2-b shows tracked markers on a rigid wing, viewed from above, for several phases of a wing motion inspired by hovering humming birds without inflow (Masateru et al. 2017). A quick rotation of approx. 160 degree is followed by smaller-scale oscillations, while the wing is performing a plunging motion with 100 mm amplitude. Due to the difficult viewing conditions (in certain positions of the wing, many marker points are only visible in one or two cameras, due to geometry and reflections), not all markers can be tracked over the whole cycle. However, the total number of captured markers (600 - 800) is always enough to allow for a reliable detection of the wing. Figure 2 c) shows a side view of the wing markers for one time-step within the rotation movement.

The particle tracers are identified in a second process. The same time-resolved minimum images that were created for the tracking of the wing markers are subtracted from the original camera images in order to remove the marker images and most of the strong reflections on the end plate. The resulting images are used to reconstruct 3D positions using advance IPR processing (Wieneke 2013, Jahn et al. 2021). For the cases without water flow, Variable-timestep STB processing (Schanz et al. 2021) was applied due to the high dynamic velocity range. Time-separations of Δ_S = 10, Δ_S = 4 and Δ_S = 1 were used for a three-iteration reconstruction. Approximately 100.000 particles are tracked after the final iteration. Figure 2 d) shows an exemplary result from a single time-step of the same case as above. The particles are given as small circles with a velocity vector, color-coded with streamwise velocity, while the wing markers are depicted as black circles with velocity vectors, also color-coded with streamwise velocity. The quick rotational movement of the wing induces strong vortices in the fluid, where velocities up to 1.5 m/s are reached.

The evaluation is ongoing. The next task will be to fit a 3D FE-Model of the wing to the captured marker cloud, in order to fully describe the flexing of the wing. The fitted model, together with the particle velocity and acceleration data, will then be used in the FlowFit data assimilation method (Gesemann et al. 2016) for the extraction of time-resolved pressure and load distributions.

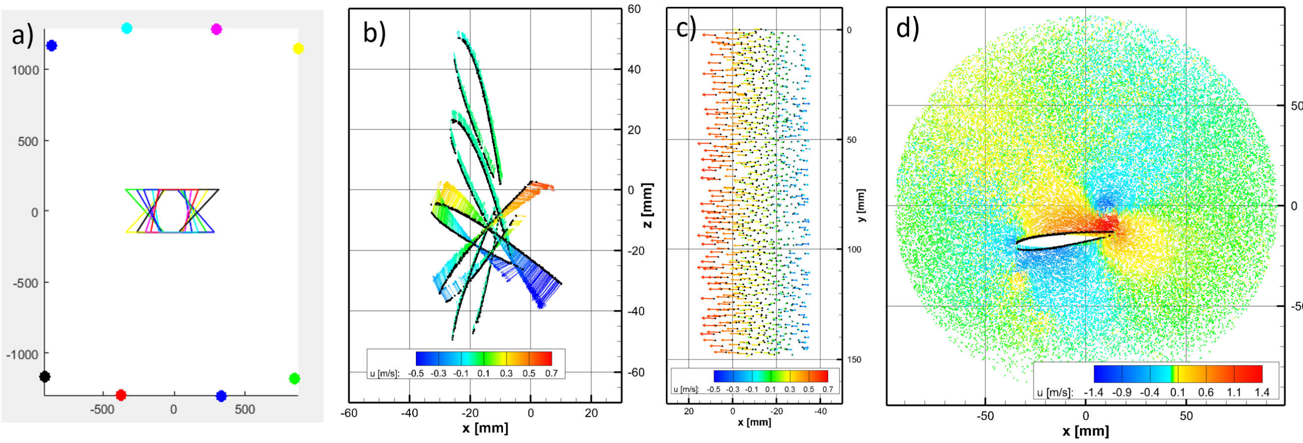

Figure 2: a) The calibrated camera setup, viewed from above. The camera lines-of-sight describe the commonly imaged volume; b) tracked wing markers with velocity vectors at four different phases of a combined ptiching and plunging movement, inspired by wing motion of hovering humming birds (viewed from above) ; c) side view of one phase of b); d) tracked particles at one time-step of the same hummin-bird-inspired movement, viewed from above. Tracked wing markers given as black dots.

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