PIV measurements on a life-size model of a peregrine falcon in dive flight conditions

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Abstract This study discusses the aerodynamics of the falcon falco peregrinus in dive flight conditions. In nature on its diving flight the peregrine falcon can reach velocities as high as 300 km/h and also maintains remarkable maneuverability. Certain diving characteristics gained from nose-diving flights of real peregrines along a dam wall enable us to investigate the aerodynamics of the diving flight conditions on a life-size model in water tunnel experiments. Visualisations of the flow via multiple-exposure imaging and PIV measurements reveal flow structures such as different vortices around the falcon body. Vortex detection via Q-criterion and spatio-temporal visualization gives a three-dimensional guess of the time behaviour of wake turbulences. The interaction of vortices around the body could lead to a significant influence of drag and lift forces on the model.

1. Introduction

The peregrine falcon is one of the world’s fastest birds. During hunting flight, when the bird is nose-diving to attack its prey it reaches velocities of more than 300 km/h (e.g. Orton 1975, Alerstam 1987). Peregrines are not only fast flyers but also maintain remarkable maneuverability at high speeds. For instance, during courtship behavior they often change their flight path at the end of a dive, i.e. they turn from a vertical dive into a steep climb. Although the nose-diving flight of peregrines has been investigated numerous times, exact measurements of the body geometry gained from real diving peregrine and the corresponding aerodynamics of the flow around this body shapes have not been determined. Therefore, we investigated the flight path and body shape of a diving falcon from a dam wall in Ponitz et al. (2014). From these data body shape information during the dive was resembled in a life-size model. In the present paper, qualitative and quantitative flow investigations via multiple-exposure imaging and particle image velocimetry (PIV) in a water-tunnel provide details about the flow structures around the falcon model body.

2. Experimental Set-up

![Image 1](https://via.placeholder.com/150)

**Fig. 1** Schematic experimental set-up.

![Image 2](https://via.placeholder.com/150)

**Fig. 2** Experimental set-up: high-speed camera (A), mirror for the rearview (B), towed model of the peregrine falcon (C), light sheet layer (D).

In Fig. 1 and Fig. 2 the experimental set-up is shown. The laser beam of a continuous Argon-Ion laser Coherent Innova 70 (3 W) passes an optical lens system to adjust the desired thickness of the light sheet. Particle images are recorded with a synchronized camera system consisting of a digital high-speed camera.
(Phantom V12.1, resolution: 1280 x 800 Pixel\(^2\)) which is equipped with 50 mm lenses by Nikon (A). The focus of the study is the flow around a life-size model (C) of a peregrine falcon in water-tunnel which is homogenous seeded with neutrally buoyant particles (90 microns). The model is towed along the test tunnel with a constant speed. A mirror (B) is located inside the tunnel with an angular displacement of 45°. Hence the camera chip orientation ensures a perpendicular and rearward view of the model. This allows capturing the pooling region behind the towed falcon model. With a recording rate of 150 frames/s the images are taken; resulting in a median particle displacement in the image planes of 5 pixel.

3. Methods

The high-speed camera (A) captures a certain and stationary illumination layer (D) through which the falcon model (C) is towed with a constant speed of 0.35 m/s. The recorded images (Fig. 3) show the temporal development of the particle movement. Obtained particle displacements are used for qualitative (streamlines) and quantitative (PIV) flow characterization. For the qualitative visualisation via multiple-exposure imaging the particle displacement over nine layered images are merged together (Fig. 5). This leads to an identification of streamlines. For the quantitative visualization via standard PIV the recorded images are evaluated by cross-correlation that provides velocity fields (Fig. 7). Furthermore, on these results Q-criteria are used as a tool for vortex identification:

\[
Q = \frac{1}{4} \left( 2S_{ij}^2 - \omega_{ij}^2 \right)
\]

with the deformation tensor

\[
S_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)
\]

and the rotation tensor

\[
\omega_{ij} = \left( \frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i} \right).
\]

When the rotation \(\omega_{ij}\) dominates the shear \(S_{ij}\) the Q-criterion results in positive values. Thus, vortex structures can be determined within the flow field.

To obtain a three-dimensional flow behavior the temporal development of the 2D-PIV results is transformed by using a third space component \(z\) instead of the time axis \(t\) (Fig. 4). This achieves a spatio-temporal visualisation (Fig. 9) of the vortices generated by the towed falcon body.
4. Results

Visualisations (Fig. 5) and PIV results (Fig. 7) are depicted for certain timesteps which are named from A to T with a separation time of 0.24 seconds from one timestep to the other. In both Figures the shadow of the towed model is visible in the lightsheet from timestep A to E. From timestep F to T the falcon stills moves in travel direction (z-axis) and the pooling region such as wake-turbulences behind the model can be observed. Fig. 6 gives a more detailed insight in the different vortices which occur via multiple-exposure imaging. Fig. 8 gives a more detailed PIV insight.

Between timesteps A and G two vorticies become visible on each side of the symmetrical body axis. Then in timestep H, the visualizations show the formation of a third vortex (Fig. 9, red colored iso-surface) behind the towed model. The first vortex (Fig. 9, green colored iso-surface) is a typical wing tip turbulence around the planform and will be present over the entire measurement. Second and third vorticies appear in the region around the fuselage body of the falcon model. From timestep I on the second vortex (Fig. 9, blue colored iso-surface) disappears and the third vortex dominates the flow.

Fig. 7 shows the quantitative flow field of the same time period via PIV. During the first timesteps (A to E) the falcon model separated by the body contour is recognizable in the vector plots (blank area). In addition to the velocity field the Q-criterion is used for vortex detection. Hence, the red colored spots reveal vorticies (rotation) whereas the blue colored spots indicate regions of shear.

On the tip of the falcon wing the first vortex can be detected in timesteps C and D. The second vortex becomes visible in timesteps E and F and disappears after timestep H when the third vortex appears (Fig. 8). Now, the first wing tip vortex and the third vortex getting closer caused by a clockwise rotation by each other (J to T).

For a better insight of the 3-D and temporal behaviour of the flow around the falcon body the timesteps of the stationary illumination sheet were transformed to the third axis z. This leads to the spatio-temporal visualization in Fig. 9 via colored coded iso-surfaces of the Q-criterion.
Fig. 5 Visualisations via multiple-exposure imaging over nine timesteps.

Fig. 6 Qualitative visualisation of the particle displacement. Each stack (G to I) consists of nine layered images.
Fig. 7 Flow field via PIV and vortex visualization via Q-criterion based detection.

Fig. 8 Q-criterion for detection of vortices. 1: Main vortex, 2-3: Body vortices
Fig. 9 shows all vortices behind the falcon model in order of the spatio-temporal visualisation method. Side and top-view show the three vortices for each side of the symmetrical model body. The main wing tip vortex (green colored) moves from top to down and from outside to inside whereas the two body vortices (blue and red colored) move lightly from inside to outside. In the vertical axis they first move down and later back in the lift direction. Significant is that both vortices show interaction in order of a clockwise rotation movement around each other. The earlier development of the first body vortex (blue colored) replaces to the second body vortex (red colored) after one quarter of the measurement time. Thus, the blue colored vortex is visible from timestep E to H and the red colored vortex appears from timestep H to T, whereas the wing tip vortex (green colored) dominates the domain over the entire acquisition time. The spatial location of certain timesteps (A, E, H, K, T) are suggested in Fig. 9 due to cross sections (grey colored dashed lines).

![Diagram](image)

**Fig. 9** Spatio-temporal visualisation of the wake turbulences around the falcon model with color-coded iso-surfaces of the Q-criterion.

5. **Conclusions**

Both body vortices have the same clockwise rotational direction as the wingtip vortex. This leads to an enhancement of the resulting circulation on each side around the falcon body in contrast to just one single existing wingtip vortex. We suppose that this kind of vortex interaction could affect the influence of the lift and drag forces on the model which is the subject of ongoing work. Further experiments might provide information about how peregrines handle high-speed dives with its remarkable manuverability.

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7. **References**

