Numerical Investigation of a Bio-Inspired Airfoil with Air-Permeable Holes

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Abstract: An airfoil derived from a bird's primary feather has been investigated numerically at low Reynolds number conditions ($Re = 30000$). It features two rows of holes along its shaft, through which air is flowing. Besides a loss of pressure difference, this air flow interacts with the separated flow on the upper side and affects the transition process within the shear layer.
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1 Introduction

Several large gliding birds feature primary feathers arranged in a cascade on their wing tips. This setup provides a reduction of induced drag in gliding and especially in soaring flight. In previous work by the authors [1] the mechanism has been investigated using a re-engineered model of a white stork's wing (ciconia ciconia). Several regions of separated flow have been seen along the primary feathers, which had been modeled as solid elements. However, actual bird feathers are air-permeable. A row of holes is located on each side of the shaft between the barbs, through which air can pass. Further, the connection between the barbs also is not airtight. This permeability has an influence on aerodynamic properties and in particular on flow separation.
In the present study, a feather airfoil with holes on both sides of the shaft has been investigated and compared with a solid airfoil using numerical simulation techniques. The geometry is shown in Figure 1. The airfoil is based on tomographic images by Eder et al. [2] and microscopic observations. In order to isolate the effects, the present study focuses only on the permeable hole rows and keeps the vanes as solid parts.

2 Numerical Setup

The simulations have been performed using OpenFOAM. The Navier-Stokes equations are solved in an incompressible formulation with a discretisation of second order accuracy in space and time. Based on the white stork's flight, the Reynolds number results in $Re = 30000$, which is low enough to allow for an investigation by DNS without applying a turbulence model.
For reference purposes, a solid airfoil with an extension of 0.25 times chord length c in span-wise, periodic direction has been considered. The mesh, based on hierarchically refined hexahedra, results in 30M cells. The outer boundary of farfield type is located $50c$ from the airfoil. For an appropriate resolution of the holes, the latter configuration requires 43M cells. Two angles of

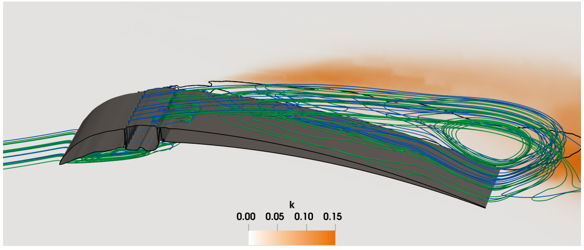

Figure 1: Streamlines from mean flow at $\alpha = 6°$ through the holes. In background indication of turbulence kinetc energy k by contours and separated flow by a black line of zero stream-wise velocity.

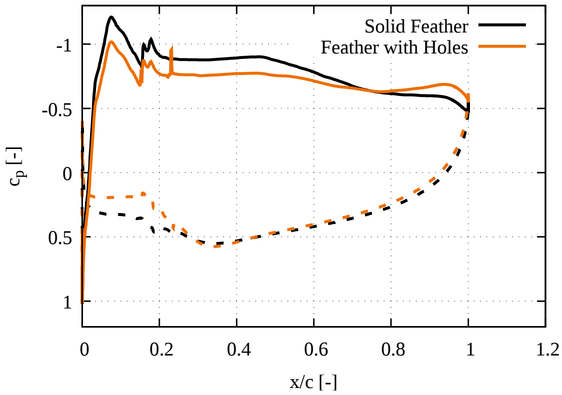

Figure 2: Mean pressure coefficient at $\alpha = 6°$. Upper side: solid line, lower side: dashed line.

attack have been considered. The first is $\alpha = 6°$, which is close to the condition of lowest sink rate, whereas the second condition is at $\alpha = 18°$ close to the maximal produced lift.

3 Results

Figure 1 gives a first impression of the flow field around the feather with holes. Streamlines through the holes are shown colored blue and green to indicate their origin from the front and the rear row, respectively. Above the rear part of the airfoil the flow separates, which is indicated by the black line of zero stream-wise velocity in the background slice. The streamlines mix into the shear layer and affect the transition process, which is indicated by the increasing turbulence kinetic energy. Also on the lower side the influence of the holes can be seen as the flow, which separates below the front part of the airfoil, shows a slightly different transition behaviour with less turbulence intensity and slightly smaller length scales when the holes are present.

The effect on the aerodynamic properties is visualised in Figure 2 by profiles of mean surface pressure coefficient. As expected an overall loss of pressure difference and thereby of lift appears due to the holes. On the lower side the difference only appears in the front part upstream of the holes, whereas in the rear part both configurations lead to nearly identical values of surface pressure. On the upper side, however, the behavior changes along the entire surface. In general, the suction on the upper side is reduced by the holes besides in the very rear part downstream of $x/c = 0.8$. The mechanism will be discussed in detail in the final paper as well as the detailed analysis of the transition process within the shear layer. The final paper also will feature the discussion of results from $\alpha = 18°$, where the flow on the upper side already experiences transition around the leading edge and the holes inject flow into the turbulent boundary layer.

References

[1] E. Tangermann, G. Ercolani and M. Klein. Aerodynamic Performance of Biomimetic Wings in Soaring Flight – a Numerical Study. In: *13th International ERCOFTAC Symposium on Engineering, Turbulence, Modelling and Measurements (ETMM)*. Rhodes, Greece, 2022.

[2] H. Eder, W. Fiedler and X. Pascoe. Air-permeable hole-pattern and nose-droop control improve aerodynamic performance of primary feathers. *J. Comp. Physiol. A*, 197(1):109-17, 2011.