56th 3AF International Conference on Applied Aerodynamics
28 — 30 March 2022, Toulouse – France

FP21-AERO2022-court

Spanwise Lift and Gust Control via Arrays of Bio-inspired Individually Actuated Pneumatic Flaplets

Alecsandra Court, Keith Pamment and Christoph Bruecker
City, University of London, Aeronautics and Aerospace Research Centre, City, University of London, Northampton Square 10, EC1V0HB London, UK, Alecsandra.court.2@city.ac.uk

ABSTRACT

Recent design and test concepts for small and medium fixed wing unmanned air vehicles (UAV) have considered new technologies of variable spanwise lift control for high-speed manoeuvring. In addition, solar powered, ultra-large wing span concepts for high altitude long endurance flights, need to be tested against gusts of variable strength along the span for their safe deployment. To address those questions in wind tunnel studies, a new concept of bio-inspired active flaplets has been developed, which can act as localised lift or gust control on aerofoils. Spanwise distributed actuators at the trailing edge are used for controlled opening and closing of the individual flaps. Causing an initial local suction and then successive blowing into the wake region, in the form of a tangential jet. This modifies the flow around the trailing edge and therefore the local circulation distribution. Furthermore, it interrupts the wake region during the time period when the tangential jet blowing happens. The segmented control regions can act independently of each other and allow for more complex control scenarios addressing localised separation cells or local gust alleviation. In addition, the concept can also be used to test the performance of aerofoils under complex inflow conditions, such as spanwise varying gusts. This can be achieved when the model is placed upstream of a wing and used as gust control unit at zero angle of attack (AoA). Disturbance patterns such as spanwise traveling waves, induced by individual flap deployment, or random artificial gust generation at different span locations can be achieved with arbitrary space-time control. The present paper covers the design, manufacture and testing of the concept with some initial results for the induced flow field when placed in a water tunnel for further research.

1. INTRODUCTION

As technology advances, engineering and aviation seek ways to ever improve design, whether it be to better efficiencies or to discover new concepts of control mechanisms. The natural world has long since been looked at as an idea source and now, biomimicry models engineering design and production on the inspiration of natural processes. A system based on the ability that birds possess, allowing them to actively pop-up wing feathers during flight to change their aerodynamic parameters, has been developed at City, University of London [1] and will be the basis of this work. Biomimicry work has been carried out at City previously, investigating the dive pattern of a Peregrine Falcon [2] and the flight control due to wing morphing, using wind tunnel tests and high fidelity simulations on idealised models. Owl inspired passive trailing edge flaplets have also been investigated at City [3] for aerodynamic and aeroacoustic benefits. While those flaplets have shown their benefit already as passive pace-makers to control non-linear instabilities in the boundary layer, the current study expands on the idea of using active control of such flaps near the trailing edge. This is to study the effect of opening and closing of the flaps, when initially aligned with the suction side of the aerofoil. Such motion patterns can generate sucessive suction and blowing into the wake, which might be of benefit to prevent incipient stall or to counteract gust-induced flow separation. As the concept is designed with multiple individual flaplets, it allows for spanwise control of such events, providing more complex patterns of response for UAVs.

The global UAV market has steadily grown in recent years and is expected to continue growing at a compound annual growth rate (CAGR) rate of 8.59% for the period 2018 to 2026 [4]. This increase in new design and test concepts for small and medium UAVs requires new UAV technologies, such as variable spanwise lift control for high speed manoeuvres. Additionally, high altitude, extreme endurance and ultra large wing span concepts need improved testing methods for spanwise gust control functionality. More complex gust patterns with varying spanwise intensity or wind direction, or with travelling wave characteristics are difficult to implement in the wind tunnel under controlled conditions. Conventional gust generation in wind tunnels is often done with a heaving wing or by two oscillating wings as in [5], temporarily redirecting the airflow to create an effective change in angle of attack downstream.

The current concept is not comparable to a morphing wing with smooth trailing edge, as it is using flaplets on a rigid body aerofoil. It can be seen as an intermediate step for fixed wing structures to achieve improved control functionality. Fully flexible structures were investigated in [6], where complex spanwise camber variation was achieved without gaps and discontinuities. Another project that showed the benefits of a fully morphable wing was [7], in which twist morphing wings were found to be more energy efficient during roll control. The project is therefore put into context with the aforementioned papers.

1.1 Scope

The paper states, discusses and explains the design process and the initial testing of a finite wing section with 8 pneumatically actuated suction side flaps. The pneumatic control permits fast flap response time, whilst the independently controllable flaps allow for spanwise flow variation. The effective performance of the spanwise flaps is analysed via particle image velocimetry (PIV) of the downstream wake section. The main objective of the project is to produce controllable and repeatable flap action and study the responsive flow pattern in a flow tunnel (water channel) to gain further knowledge of the interaction with the flow along the aerofoil and in the wake. Furthermore, the model is tested for its use as a device to generate controlled disturbances upstream of an aerofoil with complex spatial-temporal patterns.

2. DESIGN AND CONSTRUCTION OF SPANWISE CONTROL CONCEPT

2.1 Design Background

The control concept was originally developed from the finite spanwise lift control concept described in [1]. The design sought to adapt the circulation distribution along the span, using individually controllable pneumatically actuated flaps. The resultant model is currently being researched as an upstream gust generator, to produce fast response, repeatable and consistent flow disruptions, which can be controlled in their spanwise phase and amplitude individually.

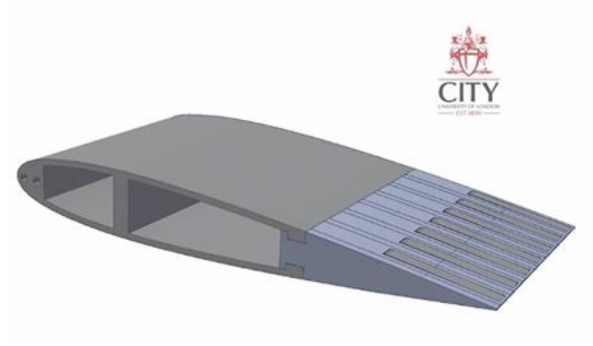

Figure 1: NACA0012 aerofoil model with individual pneumatically actuated spanwise trailing edge flaps concept. The model consists of 8 single segments in spanwise direction, which each has a flap to be actuated with a controlled opening-closing cycle.

The model consisted of removable trailing edge sections that each contained a pneumatic actuator and flap, allowing for the flaps to be repeated in the spanwise direction, shown in blue in Fig. 1 above. Each trailing edge section could slide along the aerofoil section. This design allowed for ease of access and thus improved repairability of each section.

The use of a pneumatic system was inspired by work such as [8], wherein mesostructured elastomer plates underwent fast, controllable, and complex shape transformations, at the application of pressure. Also, for aerofoil applications, there is always a constant source of high pressure flow from the bypass of the engine or from the stagnation pressure which can be used for any pneumatic control system. The use of pneumatics in this project can allow for full baromorphing structures in future work, utilising the same pneumatic system. For this project it was chosen to use inflatable air cushions as actuators, which control the deployment motion of the flaplets. For ease of use, we applied latex balloon catheters (Latex Nelaton Ballonkatheter, Balloon volume 5-10ml Praxisdienst GmbH & Co KG, Germany) as they were a 'readymade' solution to the problem. During the flap deployment, an elastic rubber band is stretched inside the cavity, which ensures to return of the flaps towards the original position flush with the wall when pressures is reduced again to ambient. This ensures a quick return towards the original position.

2.2 Construction

The flaps to be tested were based on a NACA0012 aerofoil of chord length 30cm and a finite span of 40cm. The trailing edge flap sections each had a span of 1.6cm and began at 64% chord length from the leading edge. Both the aerofoil section, as shown in grey in Fig.1 and the trailing edge sections, shown in blue in Fig. 1 had a 5mm diameter hole through them. This allowed for a threaded bar to be inserted and nuts to be added at either end to hold the sections tightly together. The nuts were recessed into capped end sections of span 8mm. A steel mounting section was manufactured and fitted into the top cap, to allow for the model to be mounted onto the traverse in the water tunnel, see Fig. 2.

Figure 2: Top end plate, shown with mounting piece fitted and recessed fittings. The mounting piece is the support for the sting as a stable connector to the traverse in the tunnel.

The model utilised 3D printed sections to allow for ease of manufacture, assembly and repairability. All the trailing edge pieces slotted into the front portion of the aerofoil and can be removed individually.

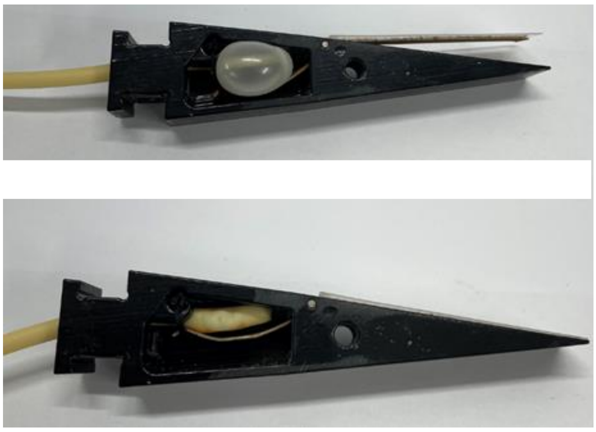

Figure 3: A single segment of the aerofoil with the balloon inside. Top: inflated situation with the flap deployed. Bottom: deflated position as the reference situation with the flap flush with the trailing edge.

The trailing edge sections were designed with a slot in for the balloon to sit into and one solid side wall, to stop the balloon affecting its neighbouring balloon at maximum inflation. The flaps were made from formed mild steel and included a soft soldered bush and pin hinge mechanism to fit into the trailing edge piece. Upon inflation, the balloon causes the flap to pivot around its hinge and move into the open position, see Fig. 3. When the pressure is reduced back to ambient pressure, the flap closes due to the elastic recoil forces of a rubber band, which is attached at the inside end of the flap and also to the segment.

Specialist fittings were manufactured from brass to mimic the tip of a syringe to allow connection to the Festo pressure lines (Festo Automation Solutions, Esslingen, Germany). This ensured the pressure lines to be securely connected to the balloon catheters.

Figure 4: Balloon-to-pressure line fitting, using the typical syringe-type Luer cone connector used in medical devices such as for the balloon catheter in use.

The control of the pneumatic system is shown in Fig. 5 below, as a schematic diagram. The pneumatic valve system referenced was developed in a previous joint DFG project together with the IME1, RWTH Aachen. It was used herein alongside an Arduino board to control the opening and closing of the individual valves in the valve block, and therefore individual flaps. The regulator, valve block and pressure pipes used were also from Festo.

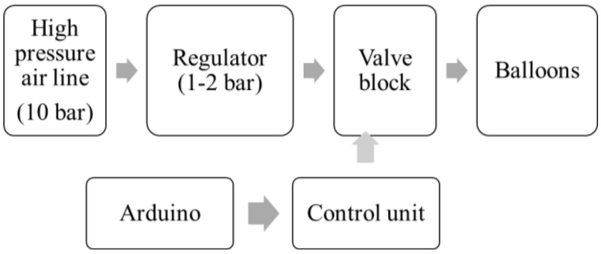

Figure 5: Schematic control diagram of the pneumatic control system.

Further iterative design improvements led to a few modifications to the design of the model after the construction phase. One such was to add thin, laser cut, Perspex sheet strips to the flaps, adhered with doubled sided tape. This ensured each of the flaps spanned the entire width of each individual trailing edge segment, thus creating less flow disturbance due to gaps between the flaps in the open position when run in parallel for several segments.

3. WATER TUNNEL TEST

3.1 Experimental Setup

The model, as described in section 2, was tested for downstream disturbance in the water tunnel at City, University of London, see Fig. 6a, b. A constant flow speed of U_0 = 5cm/s was used, corresponding to a chord Reynolds-number of $Re_C = 15\times10^3$. The flow was suitably seeded with silver coated ceramic particles of diameter 80µm (Hart Materials Limited, Tamworth, UK), used as tracer particles. The goal was to capture clear PIV results of the immediate flap and downstream wake and to quantify the effect of the flaps actuating. A 3mm LED light sheet (IL-105/6X Illuminator, HardSoft, Germany) was used to illuminate the flow around the 5th flap in the horizontal plane.

The recordings of the flow were taken with a high speed camera (Phantom Micro M310) mounted underneath the tunnel, pointed towards the LED light sheet via a mirror mounted at 45° (recordings at frame rates of 300fps, format 1280x800 px^2). Recordings were taken with different focal lengths, a larger field of view with 8x12 cm^2 was taken with a 100mm focal length and a zoomed in view with 4.5x6 cm^2, using a variable focal lens.

As displayed in Fig. 6a, the model was mounted at AoA = 0˚ in the centre of the tunnel in all axes, for initial testing. The traverse was then moved, moving the model upstream, allowing for PIV recordings to be taken at different locations downstream of the aerofoil.

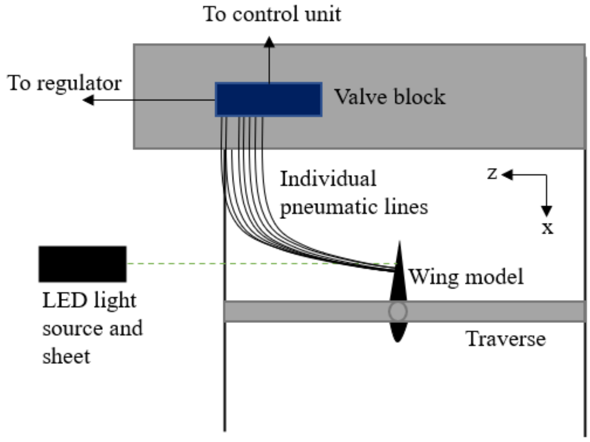

Figure 6a: Schematic of the experimental setup in the water tunnel, top view. Flow is in negative x-direction from bottom to top.

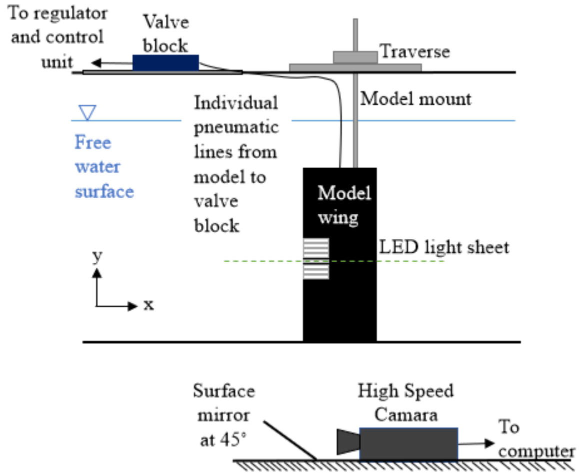

Figure 6b: Schematic of the experimental setup in the water tunnel, front view. Flow is in negative x-direction from right to left.

3.2 Actuation Control

The flaps were individually controllable via an Arduino board and Arduino IDE software connected to the valve control unit, see Fig. 7. The Arduino code outputted the instructions to the control unit and then therefore the valve block, regarding the pattern and opening or closing of each valve (total number of 20 valves). The valve block had high pressure air supplied via a regulator from a 10 bar pressure line input. The opening of a valve allowed a specified balloon to inflate, and the closing allowed for ambient pressure to return and the balloon to deflate. The typical opening time of a balloon is about 200ms, similar to the closing time by the recoil action of the rubber band. To avoid bursting the balloons, the time of high pressure is limited to about 1s in the current configuration. A time extension was possible by running the valves in an oscillating pattern with repeated short valve closing-reopening cycles. This keeps the flaps in their fully deployed configuration with only marginal motion and decreased risk of balloon failure.

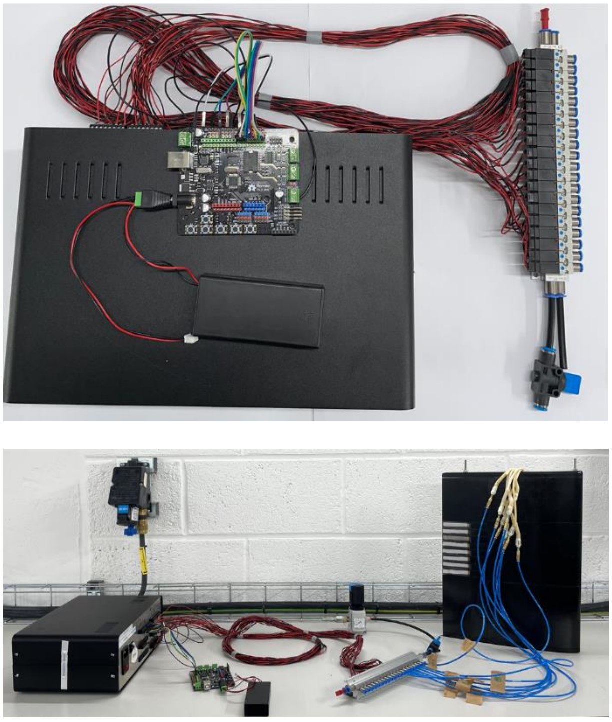

Figure 7: Valve control unit with Arduino controller (top) and shown in the lab with pressure lines connected to the balloons in the aerofoil (bottom).

3.3 Test Description

The Arduino board was programmed to run different flap patterns and duty cycles. As a reference, one of the tested patterns was all flaps up (flaps 1-8), hold for 1s and then down again, whilst capturing live images. Another pattern was two flaps at the centre up (4 & 5), two down on each side (2&3, 6&7) and the outer (1, 8) up again. This resembles a spanwise wave-type actuation pattern.

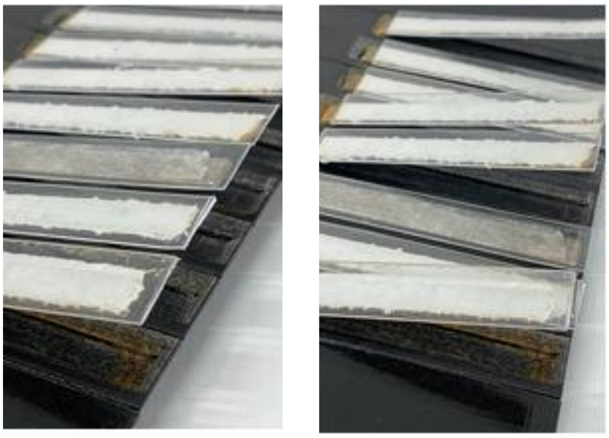

Figure 8: Typical flap actuation patterns used in the control tests. All open (left) and simulation of a spanwise wave pattern with 1,4,5,8 open (right).

A picture of the complete setup with the LED light illuminating the plane of the 5th flap is shown below in Fig. 9, illustrating the overall arrangement of the measurement equipment together with the control unit on top of the tunnel.

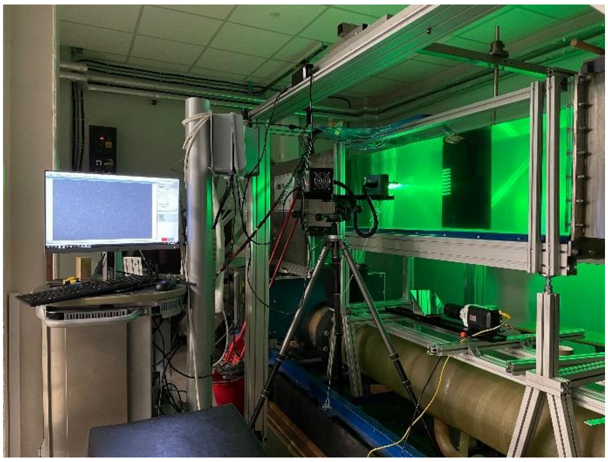

Figure 9: Picture of the water tunnel with the model inside and the optical setup for PIV measurements with LED light from the left and camera looking from the bottom

The PIV recordings were taken at different distances downstream of the trailing edge to investigate the history of the flow pattern generated by the flaps. Meaning different runs of the experiment were carried out with the model moved upstream in 7cm steps, via the traverse. The optical camera setup remained in its original position.

4. TEST RESULTS

Initial tests of the wake pattern for the actuation of all flaps simultaneous, are shown by flow visualisation pictures in Fig. 10 during the cycle of a single sequence of opening and closing of the flaps. Those pictures are generated from the recorded image sequences, taken for Time-Resolved Particle Image Velocimetry (TR-PIV). The light sheet is positioned along the mid-section of the 5th flap in the horizontal plane.

During the flap opening, a starting vortex is shed from the tip of the flap, while suction flow goes inwards into the void between the flap and the trailing edge. During the flap closure, this fluid portion is expelled in form of a jet back into the wake. The strong streamwise momentum of the jet causes acceleration of the flow at the trailing edge, into the former wake region, which is pushed further downstream. The entrainment of the jet leads further to flow acceleration at both sides of the trailing edge, which lasts until the formation of the wake begins again. Overall, this control cycle captures part of the wake fluid during flap opening and re-energises this fluid with the flap action during closure, interrupting the wake at the trailing edge with strong streamwise momentum. The current principle induces the momentum due to the squeezing effect, while the suction process entrains only fluid of low momentum from the near wake. The net effect is therefore argued to be helpful such as jet blowing, e.g. if local separation is happening.

Further downstream, the induced flow pattern evolves into a S-type flow disturbance, which is documented by the results from the TR-PIV measurements at a position of 0.5 chord length downstream of the trailing edge, see Fig. 11. The early state of the wake is easily seen on the top of the figure, by means of the streamwise elongated shear layers left and right of the wake region, which slowly oscillates in the transversal direction with small amplitude. The opening-closing cycle generates a larger vortex in the wake (clockwise rotation in blue), which is seen by the disc-like blue region on the top of the image. This region moves further downstream and induces a sinusoidal modulation in the transversal direction (shown as the thick red line in the middle section).

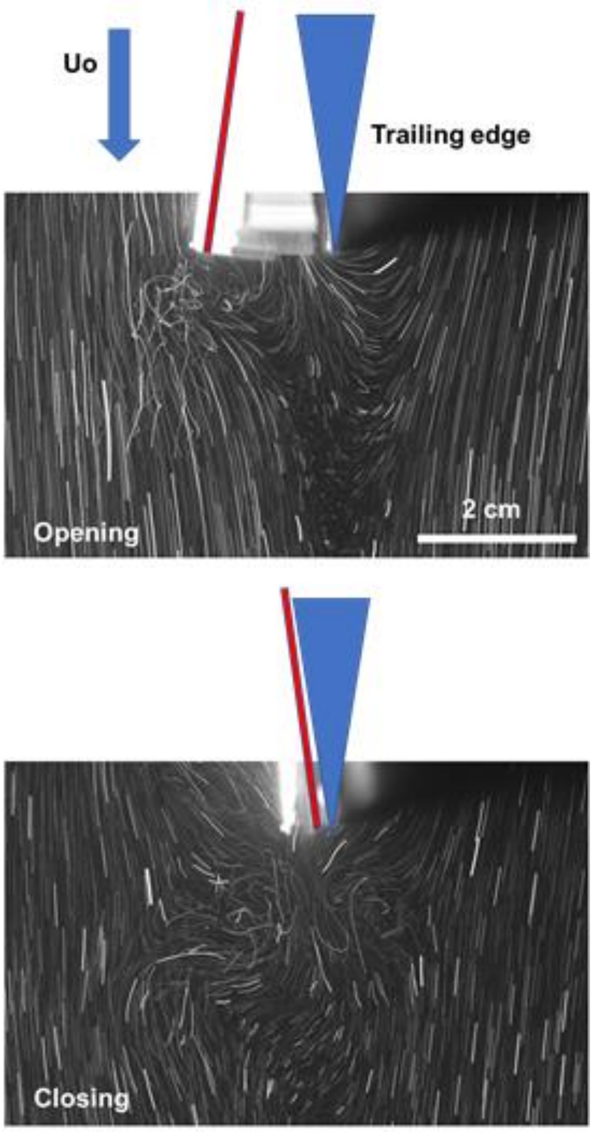

Figure 10: Flow visualisation using multi-exposed particle traces during opening and closing of the trailing edge flap row (top figure has double the exposure time compared to the bottom).

The last stage of this sequence illustrates the disruption of the wake region that the cycle has caused. There is a region of low vorticity and rather homogeneous flow that continues after the wake of the aerofoil has re-established (not shown here).

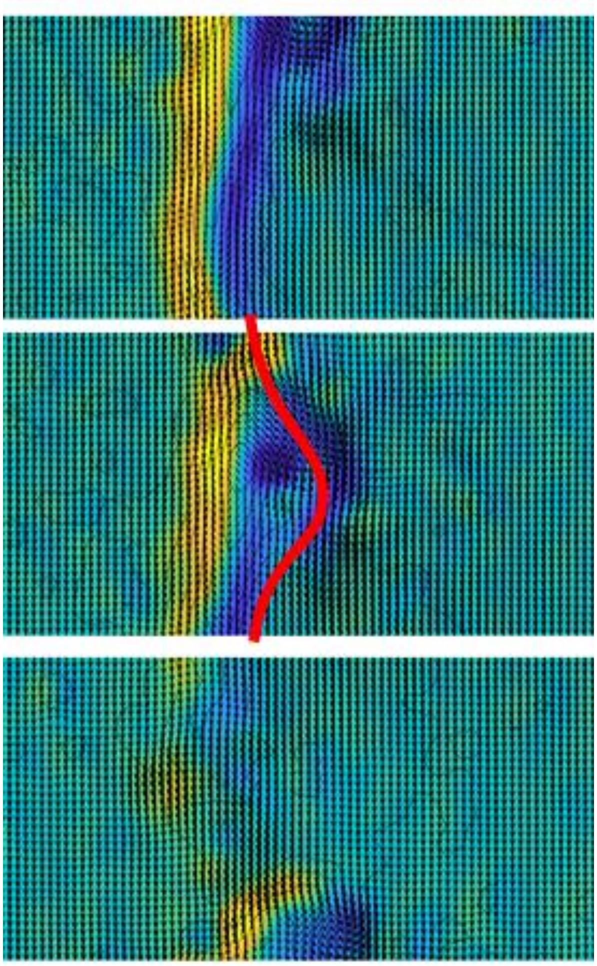

Figure 11: Velocity vectors overlaid on the color-coded vorticity field (rainbow colour distribution) for three successive time-steps of the flow, 0.5 chord length downstream of the trailing edge after flap action. (Flow direction is from top to the bottom)

5. SUMMARY AND CONCLUSIONS

The initial results presented herein show the feasibility of the pneumatic actuation principle of segmented flaps at the trailing edge for flow control. The action of the flaps is to capture low-momentum fluid from the near-wake region of the trailing edge during the opening phase, driven by the local suction in the increasing void between the flap and the surface. The closure phase then expels this fluid in form of a tangential jet, which reenergises via entrainment of the fluid near the trailing edge and interrupts the wake. The first tests were done at an AoA = 0°, which affected mainly the wake region. Further investigations will focus on the effect of increasing AoA and local interaction of the flap on the suction side with the outer flow near the trailing edge, especially for the purpose of lift control. In addition, the flaps may help to interrupt the growth of separation bubbles on the aft part of the aerofoil by preventing upstream transport and reenergising the boundary layer by the tangential jet formation.

The current configuration at AoA = 0° is further used for generation of controlled gusts in an upstream position away from test objects such as aerofoils or bluff bodies, testing their response under complex gust situations. The design allows for spatial-temporal patterns under controlled and repeatable conditions.

6. OUTLOOK

The concept using the flaplet actuators shows promise for beneficial flow control on the basis of the observed flow manipulation near the trailing edge, (suction of low momentum fluid from the trailing edge near-wake and successive tangential blowing into the wake). Further studies are required to test for lift generating configurations for higher AoA and the modification of the flow by the flap action in such circumstances. In addition, different patterns of duty cycles (opening time – fully open -closing time) will be investigated to find the optimum parameter for different control aspects, such as prevention of separation growth, or interruption of the wake relative to the characteristic time-scales of these flow formation features. In addition, different sequences of flap action need to be tested for their suction and jet formation efficiency. A single flap has a larger percentage of amount of fluid entering from the side during opening and also during closing, when part of the fluid is expelled along the side of the flaps. This effect is depending on the number of neighbouring flaps, which have similar phase in the motion cycle.

For the next stage of testing, more than one plane will be analysed using 3D Scanning PIV, allowing the capture of the flow in the complete cross sections behind all flaps in the row. The far-wake region of the current configuration with the S-type transversal flow is planned to be used for investigating the effect of such disturbances on stall cells. Therefore, the aerofoil will be installed in our wind tunnel upstream of the test section and will be equipped with the pneumatic control to generate isolated gusts of S-type transversal flow patterns. Current research is working with an aerofoil equipped with near-wall micro-pillar flow sensors to capture the interaction of these gusts with the flow over the wing.

7. ACKNOWLEDGEMENTS

The authors of this paper would like to thank Professor Schnakenberg and his team from IME1 at RWTH Aachen, Germany, for the pneumatic valve unit, which was jointly developed in a previous DFG project under reference number BR 1491/30-1. The position of Professor Christoph Bruecker is cofunded as the BAE SYSTEMS Sir Richard Olver Chair and the Royal Academy of Engineering Chair (grant RCSRF1617/4/11) which is gratefully acknowledged. We also thank Alden Midmer for his practical support in using of the water tunnel during experimental testing.

8. REFERENCES

[1] A. Court. *Trailing Edge Pneumatic Systems for Flow Control*. Master Thesis, City, University of London, 2021.

[2] O. Selim, E.R. Gowree, C. Lagemann, E. Talboys, C. Jagadeesh, C. Bruecker. *The Peregrine Falcon's Dive: On the Pull-Out Manoeuvre and Flight Control Through Wing-Morphing*. AIAA Journal, Vol 59 (10), 2021.

[3] E. Talboys, T. F. Geyer and C. Bruecker. *An aeroacoustic investigation into the effect of self-oscillating trailing edge flaplets*. Journal of Fluids and Structures. Vol 91, p. 102598, 2019.

[4] civil + structural ENGINEER media. *Unmanned Aerial Vehicle (UAV) Industry is Booming Due to Increasing Adoption of UAV In-Flight Terrorism and Increase in Demand from Commercial Applications* https://csengineermag.com/unmanned-aerial-vehicle-uav-industry-is-booming-due-to-increasing-adoption-of-uav-in-flight-terrorism-and-increase-in-demand-from-commercial-applications/ 7th December 2021, accessed from 24th January 2022.

[5] K.T. Wood, R.C. Cheung, T. S. Richardson, J. E. Cooper, O. Darbyshire and C. Warsop. *A New Gust Generator for a Low Speed Wind Tunnel: Design and Commissioning*. AIAA paper 2017-0502, 2017.

[6] A. M. Pankonien and D. Inman. *Aerodynamic Performance of a Spanwise Morphing Trailing Edge Concept*. Proc. ICAST 2014.

[7] Q. Chanzy and A. J. Keane. *Analysis and experimental validation of morphing UAV wings*. The Aeronautical Journal, Volume 122, pages 390-408, March 2018.

[8] E. Siefert, E. Reyssat, J. Bico and B. Roman. *Bio-inspired pneumatic shape morphing elastomers*. Nature Material.Vol 18(1):24-28, 2019.