Aerodynamic Wind Tunnel Investigations using a Quantitative Flow Visualization Particle Image Velocimetry System on an Active Flow Control Sweeping Jet Actuated Deployed Flap Wing Configuration

Oliver Dominik Wild

ETH Zurich, June 2020

Supervisors: Prof. Gharib (Caltech), Prof. Roesgen (ETH Zurich)

Interest in active flow control research is growing as fuel efficiency becomes more and more important in today's society. Modern aircraft are designed for emergency situations during take-off and landing as for instance an engine failure. To allow for such occurrences as well as to achieve low take-off and landing speeds, the wings are oversized for cruise conditions where a lower lift coefficient value would be sufficient. Oversized wings increase the structural weight resulting in a higher fuel consumption and fuel weight. A larger aircraft weight requires a higher aerodynamic lift, causing the drag to increase as well, and thus reducing the fuel efficiency of the airplane. Employing active flow control selectively in all critical flight conditions allows to achieve lower take-off and landing speeds as well as an appropriate design for emergency situations with a much smaller wing optimized for cruise conditions. This leads to a reduced structural weight and a lower fuel consumption resulting in a higher fuel efficiency.

Sweeping jet actuators — also called fluidic oscillators — are believed to be very efficient AFC devices. They resemble steady blowing as both methods require a steady compressed air supply, but fluidic oscillators are more efficient in terms of compressed air consumption [1]. Figure 0.1 shows a schematic drawing of a sweeping jet actuator, note that no moving parts are required in the internal sweeping jet actuator design. Highly pressurized air is provided at the left side in Figure 0.1 which then flows out via the interaction region through the outlet on the right. Within the interaction region, the flow attaches to one of the two walls due to the Coanda effect, in the Figure it is attached to the upper wall. The back flow through the feedback path causes the jet to detach from this wall due to the increased pressure at the control port and reattaches at the opposite wall [2]. This process repeats itself leading to a two-dimensional, self-sustaining systematic oscillation [1]. The jet oscillation frequency mainly depends on the feedback path length and the pressure ratio between the inlet (air supply) and the outlet of the actuator. The oscillation spanwise sweep angle is determined by the detailed actuator design [1, 3].

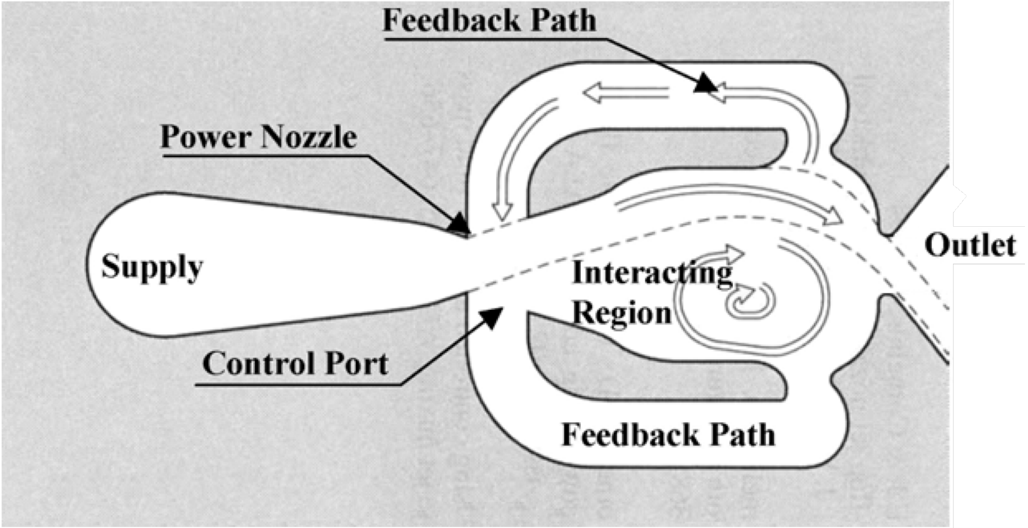

Figure 0.1: Drawing of the internal design of a sweeping jet actuator showing the air supply on the left and the outlet nozzle on the right. As a result of the Coanda effect, the flow attaches in the interaction region to either of the two walls and oscillates between them due to the feedback air flow developing an oscillating outflow at the actuator outlet [2].

The wind tunnel model used for all experiments in this research project is a low aspect ratio wing with a semi span of roughly half a meter and a wing sweep of 30°. An 8° angle of attack with a flap deflection angle of 30° were chosen as this configuration simulates an aircraft during take-off or landing very accurately. 12 jets are distributed over the span at 80% of the chord length. The main research question of this project is how the spanwise jet location influences the flow separation on the flap hinge and how this affects the aerodynamic force production of the entire wing. Three measurement techniques are applied: Particle Image Velocimetry (PIV) measurements capturing the flow state, surface flow visualization on the wing suction side with tufts, and wind tunnel force balance experiments to measure the flow impact on the forces.

The PIV setup consists of three components: The seeding, the illumination source, and the camera. Small soap bubbles with a diameter of 10 to 60 micrometers are added to the flow as tracer particles, a pulsed laser with a wavelength of 532 nanometer is used to illuminate the plane of interest, and the camera capturing the PIV image frames is mounted inside the wind tunnel at the ceiling of the test section. Two planes are investigated, which are located directly at the outlet of the fifth jet (counted from the wing root) which is located approximately at the center of the semi span, respectively at the outlet of the eleventh jet close to the wing tip, both positioned perpendicularly to the flap surface. The wind tunnel free stream speed is chosen to be 15 m/s which is the lowest Reynolds number independent velocity, allowing to study the largest range of extended mass flow rates. The extended mass flow rate is a measure for the mass flow through the sweeping jet actuators with respect to the mass flow in the freestream.

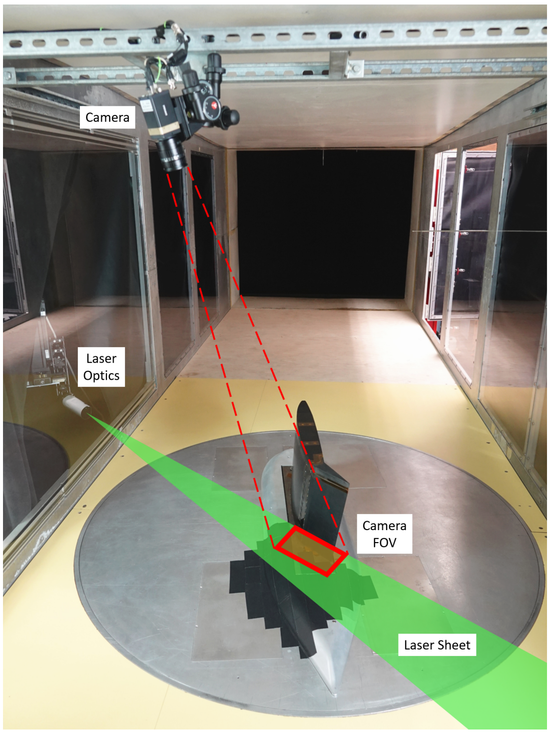

Figure 0.2: PIV setup in the John W. Lucas Wind Tunnel at Caltech. The laser system is positioned outside of the wind tunnel and illuminates the PIV plane with a laser sheet (green). The camera is located above the PIV plane in the tunnel and oriented perpendicularly to the PIV plane to obtain an undistorted field of view (FOV).

From the results of the experiments carried out in the scope of this research project, the twelve sweeping jet actuators can be divided into three spanwise jet location groups. These are the wing root jets, the center jets, and the wing tip jets. The wing root jets are best for take-off, as they achieve a high lift increase at an additional drag that results in a slight decrease of the glide ratio. For take-off, a high lift coefficient is required, but the drag should not be too large as this would restrict the acceleration of an aircraft. The jets closest to the wing tip should also be deployed during take-off and in emergency situations during cruise flight as they enable an increase in the glide ratio leading to a higher aircraft efficiency. Finally, the center jets typically increase the lift and drag so that the glide ratio decreases compared to the wing root and tip jets what is vital for the approach and landing phases during flight. Note that these three major jet location regions are not strictly defined as a result of the lift and drag coefficient behavior, but the coefficients transition rather smoothly between the different regions.

The tuft measurements revealed a general spanwise flow on the flap pointing towards the wing tip. By activating a wing root jet, the spanwise flow can be reduced as these jets act like a fluidic fence. The PIV experiments revealed the highest impact on the flow field coming from the center jets. The center jets manifest high lift gains due to their ability to prevent separation on the flap and as a result the wake shrinks. Jets located further outside towards the wing tip only alter the flow field in the wing tip region starting from the given jet position as an impact against the spanwise flow direction is only detectable over one jet spacing inwards but much further outward towards the tip. This was shown with a single active jet positioned at the PIV plane that partly reattaches the flow on the flap surface in this plane, but an influence in the flow field coming from jets closer to the tips is hardly measurable.

Jets located at the wing tip modify the flow field on the upper flap surface at the tip in a way that reduces the vortex strength of the wing tip vortex. Most likely, this happens due to the fluidic fence effect occurring at the wing tip what mitigates the pressure compensation taking place between the pressure and the suction side of the wing. This results in a lower induced drag leading to an increase in the glide ratio what also enhances the fuel efficiency of an aircraft during take-off.

The value of the extended mass flow rate depends on the spanwise location of the PIV plane as it was shown with all jets activated. In the center of the wing semi chord, a larger mass flow rate is required to reach a fully attached flow whereas closer to the wing tip a slightly lower mass flow rate suffices. It was shown that the extended mass flow coefficient is not a constant due to 3D effects like the tip vortex or the fuselage affecting the flow field and the pressure field over the wing. Furthermore, the high wing sweep angle of the wing used in this study also has a major impact on this value.

It becomes apparent from the experimental results of this research project that already a single active jet has a large impact on the aerodynamic forces as well as on the flow field on the flap. A single jet is able to reattach the flow on the flap locally and increases the total lift of the wing. However, in any case a wake remains present above the locally attached flow region because of the fact that in both spanwise directions where no jets are activated a wake remains which then just shrinks in size and slightly translates away from this locally attached flow region. By turning on all jets, the whole wake can be removed if an extended mass flow coefficient equal to or exceeding a given critical extended mass flow coefficient is obtained. A further increase of the mass flow rate when the flow is already fully attached results in supercirculation. Supercirculation leads to a linear lift increase with a rising mass flow rate resulting from an increased air speed on the wing suction side. Nevertheless, separation control in order to eliminate the wing wake is the most efficient region for AFC systems as already stated by Hirsch [1].

Bibliography

[1] Hirsch D., An Experimental and Theoretical Study of Active Flow Control, 2017, PhD Thesis (Caltech).

[2] Raman G. and Raghu S., Cavity Resonance Suppression Using Miniature Fluidic Oscillators, 2004, AIAA JOURNAL Vol. 42, No. 12.

[3] Schmidt H., Woszidlo R., Nayeri C. et al, Fluidic Oscillators for Bluff Body Drag Reduction in Water, 2016, AIAA 54th AIAA Aerospace Sciences Meeting.