# TEST AND INDUSTRIAL ASSESSMENT OF ACTIVE FLOW CONTROL INTEGRATION IN ORDER TO INCREASE HIGH - LIFT PERFORMANCE

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**Abstract**

Active Flow Control (AFC) is one of the envisaged future elements of better aircraft performance. Large efforts have been made up to date to investigate different AFC concepts. However the focus was mainly on basic aerodynamic principles. In light of more comprehensive overall aircraft feasibility studies an Active Flow Control wind tunnel test campaign in collaboration with the Technische Universität Berlin was conducted in the Airbus Low Speed Wind Tunnel test facility in Bremen. The AFC system, which was designed by the TU Berlin, was integrated into an industrial high-lift half-model. As AFC concept pulsed blowing was selected and the air was blown trough slots incorporated in the inboard and outboard flap shoulder of this high-lift configuration. By adjusting the gap via spoiler droop the flap was made receptive to AFC by deteriorating the high-lift setting and supporting therewith separations. In the following it was shown that the AFC system was capable of eliminating those flap flow separations. In this paper the aerodynamic performance will be evaluated and compared to the reference setting without active flow control. Additionally, the performance will be analyzed with respect to various AFC system parameters, such as mass flow rate, pulse frequency and gap settings. Concluding, the use of active flow control in order to enhance the high-lift potential seems feasible from an aerodynamic point of view. However, the aircraft integration and its associated constraints with respect to space provisions, energy supply and consumption have to be considered as well. Therefore, a concept for active flow control integration into a trailing edge flap of the generic type (FNG) will be described herein. For actuation a self-excited fluidic diverter was chosen and implemented into the leading edge box of the inboard flap. Synergies were generated by using the cavity between by the structural support of the actuator, the flap front spar and the flap covers as supply air tubing. An assembly concept was developed focusing on low weight as well as low manufacturing complexity. Compliant with the requirements, the new system can be retro-fitted into the existing flap without changing the main flap center-box structure. With respect to the aircraft system integration, this work developed a concept for an efficient air supply with minimum weight increase. Several multidisciplinary aspects had to be treated in an iterative manner. In order to study those interactions, a program was developed, which calculates total pressure loss trough the whole AFC system as well as the characteristic flow properties in the plenum. With this set of information sensitivity studies showed off-design behaviour of the system through the whole flight envelope to be acceptable. In the end it could be shown that the weight increase is also within an acceptable level.

## 1. INTRODUCTION

The performance requirements for commercial and military aircraft are growing with respect to energy efficiency, improvement of takeoff and landing performance, noise reduction, safety and commercial constraints, to mention the most important parameters. Especially the design of the high-lift system for a new aircraft configuration is a key parameter for success or commercial failure. Due to overall aircraft design trades the high-lift system complexity is being reduced to highly optimized single slotted flaps and slats. Their achievable gains, are mainly limited by separations. Therefore, keys for further improvements have to be found in the flow physics. Breaking the existing constraints by using a method of Active Flow Control AFC will then have an effect on new geometry possibilities, opening a wide range of design solutions. In contrast to passive flow control systems, AFC doesn't create a drag penalty in off design scenarios, when no flow control is needed. This paper is structured in two main sections: The first section focuses on the aerodynamic feasibility of active flow control and discusses the results of a wind tunnel test of an Airbus high-lift half-model with an integrated pulsed blowing active flow control system designed and integrated in the flaps by the TU Berlin. The summarized test conditions, results and figures are taken from the test report [1], which is not public. However, an extensive analysis of the test results was presented by Bauer et al. [2]. The second part is presenting the results of a white paper conceptual study, dealing with the integration of such an AFC system into the trailing edge flap of the generic single aisle aircraft FNG in flight scale [3]. The intention of this publication is to link both activities together. Introducing with a brief overview of the wind tunnel test campaign, mainly conducted by Airbus departments within the aerodynamic domain and the aerodynamic department of the ILR within the Technische Universität Berlin, the test description is followed by a discussion of the challenges in transferring the information from this purely aerodynamically driven test to a global aircraft analysis level.

## 2. WIND TUNNEL TEST

From [1] the experimental test conditions are summarized herein and presented in the following section. A preliminary test was carried out in June 2008 in order to find an appropriate flap setting for separation control. Subsequently, an elaborated wind tunnel campaign was conducted in February and March 2009 in the low speed wind tunnel test facility of Airbus Operations GmbH in Bremen in collaboration with the aerodynamic department within the ILR of the Technische Universität Berlin. The wing of the half-model with the scale of about 1/13$^{th}$ compared to a full scale aircraft was equipped with leading

Figure 1: Industrial half-model in Bremen Low Speed Wind Tunnel (BLSWT) [1]

edge slats, trailing edge flaps and droop spoilers. The flap gap and overlap was referenced to the spoiler trailing edge and therefore the spoiler droop angle dominated the setting. The wind tunnel with an atmospheric circulation was sped up to a Mach number of 0.2 yielding to a Reynolds number of about 1.6 million. Nowadays, an industrial high - lift design is optimized with two- and three- dimensional computational fluid dynamic tool-chains, as well as high Reynolds number wind tunnel tests and a broad experience obtained by various aircraft programs. Therefore, hardly any flap separations occur in the normal flight envelope. However, in order to fully exploit the potential of the shear layer exciting vortical structures, past research [4][5][6] has shown that the best lift benefits are associated with the elimination of large regions of flow separation. In order to account for this deficit two scenarios where investigated in this campaign: **A:** The flaps were rigged in the optimized flap setting, comprising of a gap and an overlap, referenced to the trailing edge of the drooped spoiler. The flap deflection angle was set to 45° and the spoiler was drooped about 13°. Subsequently, without changing the flap position, the spoiler droop was decreased to a value of 6° resulting in a different setting with a strongly increased gap. This unfavorable gap yielded to a partially separated flap representing a target for the AFC system. **B:** For the second scenario the flap deflection angle was increased by 5°, resulting in a fully separated flap over the full range of angle of attack. For this deflection the spoiler setting was adjusted again to a slightly smaller spoiler droop of 11° compared to the 13° in the optimized configuration. The fluidic actuator system mainly consisting of the piping, the valves and the control units were developed and integrated by the Aerodynamic Institute of the Technische Universität Berlin. Both inboard and outboard flaps incorporated an active flow control system with segmented slots. Due to the challenging assembly volume the valves had to be fitted into the fuselage of the model. This inevitable constraint caused high pressure losses up to 90%. Like in previous publications [6] a square signal was desired. However, this square function must have been deteriorated in the small piping, which was necessary to duct the pressurized air through the belly along the flap shroud into the 21 segmented actuator chambers. The actuator chambers were subject of an elaborated aerodynamic design done by the TU Berlin in order to achieve a span-wise evenly distributed jet velocity. The mass flow of the system was adjusted by 5 control valves, which were linked to a valve for each actuator chamber in the flaps. The pressure was measured in the latter valves and fed back by a monitoring unit in order to adjust the control valve pressure. The tangentially inclined exhaust slot of each actuator unit was positioned at about a quarter of the local chord, which was based on previous experiences made by the TU Berlin and also from the pressure distribution plots obtained from the pretesting in June 2008. Fluorescent tufts were used to visualize vortical flow regions and separating areas. Concerning the active flow control parameters, a non dimensional momentum jet coefficient in the range of 0% up to 1% was tested. This parameter is the squared value of the timely averaged jet exhaust mass flow, normalized by the product of the free stream dynamic pressure, the free stream density, the wing reference area as well as the cross-sectional area of the jet.

$$c_\mu = \frac{\dot{m}^2}{q_\infty \cdot \rho_\infty \cdot A_{ref} \cdot A_{slot}} \quad (1)$$

The non-dimensional frequency ranged from 0.09 up to 0.6. The $F^+$ value can be seen as a Strouhal number of the vortical flap actuation. The product of the actuation frequency and the flap chord length is therefore normalized by the free stream tunnel velocity. The upper limit was superimposed by the maximum capable frequency of the solenoid valve in the fuselage.

$$F^+ = \frac{f \cdot c_{flap}}{U_\infty} \quad (2)$$

Both open- and closed- loop control [7] methods were conducted in the test, while the open loop test shall solely be discussed in this publication. Additionally, tests were performed with phase angle variations of the different actuator segments. The frequency and the duty cycle (DC) were varied in order to assess their influence. The DC is the system operating time within one period, normalized by the full period duration. Thus, a duty cycle of one represents a steadily operating system. Due to the fact that the tested Reynolds number was lower than in flight, transition fixation was applied on the flap leading edge at about 5% local flap chord assuring a more realistic turbulent flap flow.

## 3. RESULTS OF TEST

The results of the wind tunnel test, explicitly described in [1] are highlighted and summarized in following section in order to bridge the gap between aerodynamic testing and the conceptual design of a large scale system. The optimized reference case (**A**) was limited in its maximum lift capability by an outboard wing separation and the associated flap flow only separated partially in the linear regime, while an almost fully attached flow was seen close to the maximum lift coefficient. By the gap increase the adverse pressure gradient was enlarged and the performance of the flap was significantly reduced over the whole AoA range. With active flow control applied to this scenario the lift in the linear regime was identical compared to the optimized reference configuration, while the AFC system exceeded the lift capability of the reference configuration in the non-linear regime. This effect results from the improvement of the outboard main-wing flow, which was achieved by an enhanced flap performance in this region due to AFC. From testing the same large gap setting with and without flow control one can summarize that the improvement of the flap flow created strong lift gains in the linear regime, while the CLmax regime improvements were small. Steady blowing methods with a duty cycle of one showed similar results in the order of same magnitude, however with an increased mass flow consumption due to the continuous operation of the jet. The second scenario (**B**) with an increased flap deflection angle, as discussed in the previous section, showed very similar results compared to scenario **A.** The reference configuration with a larger flap deflection and a slightly smaller spoiler droop showed a mainly fully separated flap. Unfortunately, with the highest $C\mu$ tested the active flow control system was not able to completely recover all separations with AFC. Figure 2 shows the

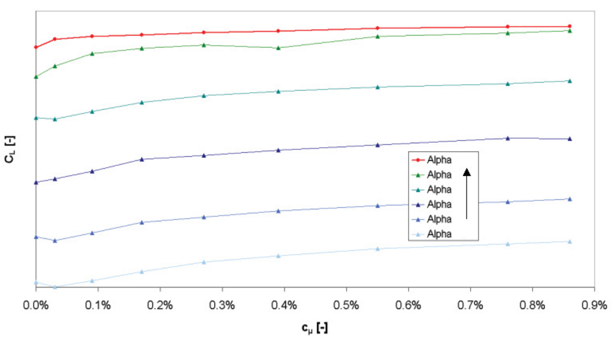


Figure 2: Quantitative CL with respect to momentum coefficient for different angles of attack [1]

qualitative lift level over the momentum coefficient on the abscissa for scenario **A**. It can be seen that high angles of attack cases show a very early convergence effect, while this is delayed with respect to smaller AoA in the linear range. It was reasoned that the early saturation tendency can be traced back to the inevitable deficits of the test, which can be mainly contributed to three aspects:

- Very high pressure losses in internal system
- Deterioration of pulse signal due to long distance between valve and exhaust
- No separations existent in the flight envelope and the flap shape was not optimized for AFC

Consequently, this paper will briefly describe the results obtained with respect to the sensitivity of the major AFC parameters, namely actuation frequency and duty cycle as well as the efficiency of the control system rather than discussing absolute values. It is believed that the impact of the three issues raised above can be drastically reduced by implementing the active flow control concept into early design stages. Here it is therefore more important to raise the awareness of potential challenges in the global aircraft domain. For an efficient use of active flow control it is important to get a sufficient margin of lift associated to the system, while using a minimum of energy. This is especially important, when using the flight propulsion system as a bleed air source for the AFC energy supply, since it is usually in an approach idle mode during the landing phase where high - lift values are desirable. Due to the limit testing time only two major reduced frequencies were investigated, namely $F^+$ = 0.34 and 0.51. The test result revealed a slight improvement towards the higher actuation frequency. However, as mentioned in [1][2] due to the design of the system structure the momentum is linked to the frequency and therefore it was not possible to operate different frequencies for a constant non-dimensional momentum coefficient. For the scenario **B** a duty cycle study was performed and due to [1] the results were somehow unexpected. It was shown that the lift performance increased with the duty cycle up to the level of steady blowing. This indicated that the beneficial pulsed blowing effect could not be fully exploited**.** Again looking at the signal passing through narrow long pipes associated with large losses, it is not surprising that a strong deterioration of the AFC exhaust pulse diminishes the excitation effect. Figure 3 shows the lift due to AFC divided by the non- dimensional momentum coefficient, representing the effectiveness of the AFC system for scenario **A**. It can be seen that an optimum is located in the region of about 0.2%$C\mu$.

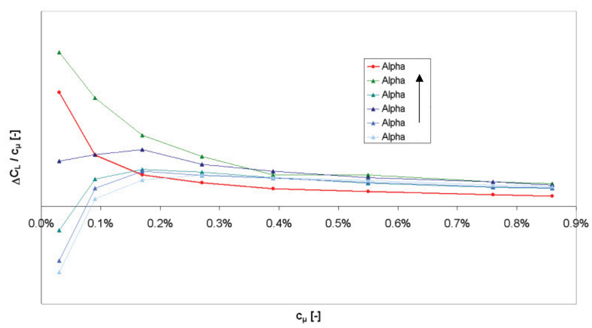


Figure 3: Lift benefit divided by momentum coefficient with respect to absolute momentum coefficient [1]

Figure 3 shows that for high angles of attack a small momentum is more efficient than for low angles of attack. However, doubt remains that this convergence generally applies. Associated with high pressure losses and the high likelihood of strong shock patterns chocking the flow in the internal piping may have contributed significantly to those convergence effects. Partially losses were accounted for by an empirical method as discussed by Bauer [2], but this has to be further addressed when looking at large scale applications. For the paper based study on aircraft level a $C\mu$ value of 0.2% and a $F^+$ actuation frequency of one was chosen. The momentum coefficient decision was based on the most efficient operation shown in the test campaign, while the frequency was picked due to the argumentation of various researchers, who found a non-dimensional frequency in the order of unity to be the most effective shear layer excitation method [8][9]

## 4. MULTIDISCIPLINARY AIRCRAFT ASPECTS

In a study conducted within Airbus in collaboration with the Technical University of Braunschweig [3] a concept was developed, which focused on the following aspects :

- Methodological concept development for an AFC integration
- Choice of fluidic actuator concept
- Principle design of actuator according to the available assembly volume, manufacturing aspects and operational constraints
- First preliminary analysis of structural integrity with special emphasis on the slotted structure
- Conceptual design of energy supply routes and a discussion of potential energy sources with an additional analysis of associated pressure loss predictions
- Preliminary weight assessment

The following sections are the essential parts of this study [3].

### 4.1. Technology platform

The system was integrated into the generic FNG aircraft. ("Flugzeug nächster Generation") This single aisle aircraft was developed in 2001 within a LuFo project and ever since it is in the focus of collaborative research with external partners. The trailing edge flaps, which where designed by the DLR Braunschweig [10], were assumed to have an increased deflection angle of 40° in the full landing setting with AFC. The aerodynamic performance of the AFC method was not part of this study and was therefore assumed to be equal to the test results for a $C\mu$ of 0.2%, as presented in Figure 3.

### 4.2. Methodological concept development

A function structure according to [11] was developed, giving an overview on the most important systematic AFC aspects. It was helpful to abstract the system into major functions and essential subfunction. This approach was linked to a morphological box study balancing the potentials of various methods and ideas. This structure can be the fundamental basis for a following system safety analysis, which is important when looking at the integration of active flow control.

### 4.3. Assembly room and structure

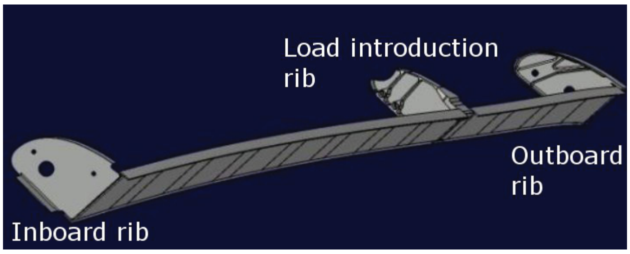


Figure 4: Model of basic leading edge box structure [3]

Due to the lack of AFC integration experiences the system was integrated into the FNG inboard flap geometry with a large assembly room and a nearly constant cross-section. In order to evaluate the potential of retrofitting an active flow control system, it was decided to freeze the assembly room structure downstream of the flap front spar. This left a leading edge box, shown in Figure 4, constrained by two end ribs and a load introduction rib. The external flap nose surface CFRP panel is riveted to the upper and lower shoulder of the flap front spar and closes up the assembly volume. The flap tracks are connected to the inboard rib and the load introduction rib, partially shown in Figure 4.

## 5. FLUIDIC ACTUATOR CHOICE

The fluidic actuator is required to perform the two major functions of creating a pulsating air jet as well as providing the required exhaust slot. In the course of the morphological box evaluation and the literature research the fluidic diverter concept was chosen. In various publications D.E. Culley from the NASA Glenn Research Center and his colleagues described this fluidic device [12][13][14][15][16][17], which was designed for active flow control with the major goal of jet engine performance optimization. A detailed description of the bistable flow diverter functionality can be found in [12] and is shortly summarized in the following as well as schematically depicted in Figure 5.

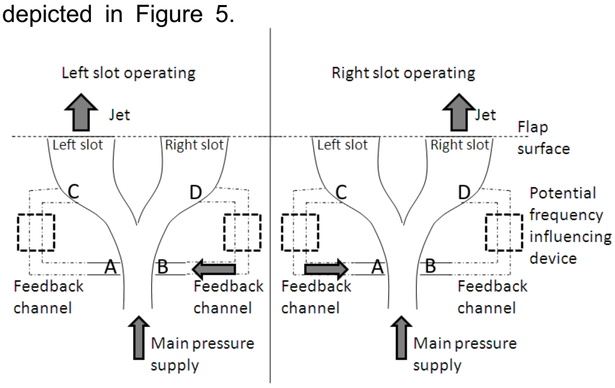


Figure 5: Schematic illustration of fluidic diverter

Compressed air is ducted to the main pressure supply in Figure 5, facing a pair of symmetrically arranged channels ending in a left and right slot. Initially slot-symmetric flow is switched to the right exhaust by applying a short pressure pulse to the left control port, labeled with the upper case letter A. The flow equilibrium is reached very fast and the switching process is driven mainly by the internal channel geometry. The current flow state is supported by the stabilizing Coandă wall geometry above each control port. The exhaust slot can be swapped by applying a short pressure pulse to the opposite control port (letter B Figure 5) Therefore, the actuator constantly emits a jet through one of the two slots. In [17] the control port is connected to another opening (C or D in Figure 5) shortly before the jet reaches the external environment. The interconnection schematically depicted in Figure 5 (e.g. A-C) presents a feedback channel, which makes it possible to deliver self-generated pressure pulses to the control ports in A and B, respectively. As explicitly derived in [18] the actuation frequency of the diverter can be reduced by the installment of flow capacitors and flow resistors. In an analogy to electronic resistor- capacitor circuits due to [18] the resistance is driven by the pressure loss, while the capacity is mainly depending on the volume of the feedback. For this study external dimensions and performance-test results, were provided by Bauer. (TU Berlin) Based on his studies, focusing on the actuator development and testing, Bauer provided the necessary information regarding an actuator similar to [19]. On this basis the author was able to develop a fluidic actuator integration concept based on the same principles discussed above, which is suitable for the flight scale application. Reference [19] uses valves for pneumatic control port pulses, however for this study it was assumed that the integration of a feedback loop is possible when considering the aircraft program design effort as well as internal and external research. For clarification Figure 5 shows a schematic fluidic flow diverter containing the major aspects mentioned by [12][13][14][18][19].

## 6. CONCEPTUAL ACTUATOR DESIGN

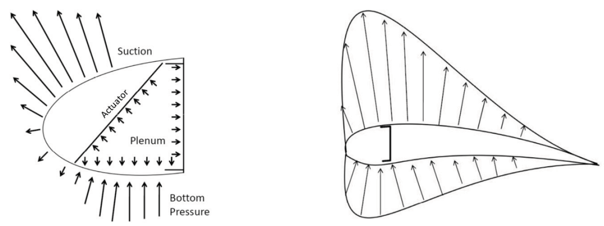


Figure 6: Schematic view on actuator integration [3]

In Figure 6 a drawing can be seen, which shows a cross-sectional view on the actuator integration. The view represents a cut-section of the leading edge box with an integrated actuator. Except for the diagonal wall, all structure is nearly unchanged in comparison to the legacy structure. This wall, representing the actuator, separates the leading edge box in two compartments, creating a pressure plenum surrounded by a part of the bottom CFRP panel, the actuator and the front spar. Beneficially is the fact that the internal pressure has no influence on the external shape of the flap suction side. Thus, the aerodynamically more critical region is not subjected to a pressure induced deformation. With respect to more optimized flap settings the gap tolerances become more stringent and a pressure deformation has to be avoided. Additionally, structural bird strike functions and the integrity of the actuator are not directly linked. Looking at the bottom panel, the external pressure and the internal pressure oppose each other reducing the absolute pressure acting on this surface. Similar to the wind tunnel test campaign the slots were tangentially inclined with an angle of about 30°. This inclination is partially pre-adjusted with this actuator arrangement as shown in Figure 6. This setup provides the possibility to fasten the actuator to the front spar, which provides the strongest support in this assembly room. The assembled actuator arrangement is depicted in a more detailed way in Figure 7. The actuator is manufactured from aluminum, which is prevented by a glass layer from oxidizing due to the direct contact to the CFRP material. The diagonal actuator support wall is divided into two components. This provides the possibility to separately fasten the lower and upper part of the actuator to the leading edge box panel for a span-wise varying flap height. The riveted interconnection of both parts excludes high tolerance levels and is easy to manufacture. The slots and the upper part of the actuator plane are all incorporated in one single milled aluminum piece. This assures that the force-flux, circling the plenum boundary, leaves out the nose panel.

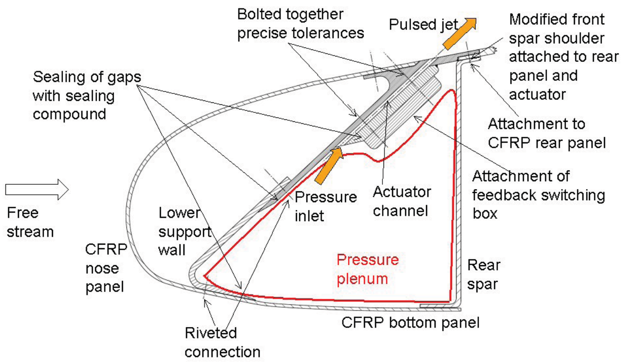


Figure 7: Detailed view on actuator integration concept

The channels for the diverter and the switching mechanisms are created by bolting a milled aluminum block onto the actuator support wall. One can imagine a flat surface representing the actuator back wall. By placing a profile with an u-shaped cross-section downwards on the flat surface a channel with four walls is created. In order to prevent leakages all gaps and fastening connections are sealed. The front-spar had to be modified in order to provide enough space for a rivet connection with the actuator. The effect of this modification on the span-wise flap bending was neglected due to minor changes in the Steiner part of the moment of inertia. The interaction of slot stresses with rivet stresses was prevented by distancing all rivets at least 10 mm away from free edges or holes.

## 7. SLOT STRUCTURE ASSESSMENT

### 7.1. Assessment of the legacy structure

A simplified leading edge box model was built and the ultimate loads and displacements were transferred from a comparable aircraft to the FNG inboard flap. A basic FEM model without slots was computed with NASTRAN/ PATRAN using a typical cross-section. It was assumed that the front spar web would only experience deformations its basic plane, meaning no deformations in flow direction were accounted for. Besides the superimposed vertical displacement function, the external aerodynamic pressure was applied to the model. A high tensile stress was found in the designated slot plane at the span-wise position, corresponding to the largest displacement. Additionally, compressive stresses were found in the region of the outboard track. This is due to the S-type flap deformation as shown in Figure 8.

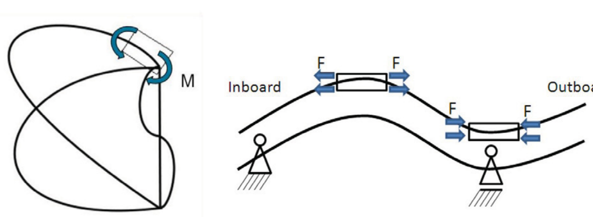


Figure 8: Schematic leading edge nose deformation

Additionally, on a much smaller scale, a chord-wise moment was identified. Due to the pressure difference between upper and lower side the flap nose is prone to bend upwards creating a S-type deformation of the flap front spar cross-section. This pattern is mainly driven by the stiffness of the flap shoulder.

### 7.2. Analytical slot assessment

As illustrated in Figure 9, the tensile forces and moments were evaluated at the span-wise position with the highest displacement in order to conduct an analytical slot stress assessment.

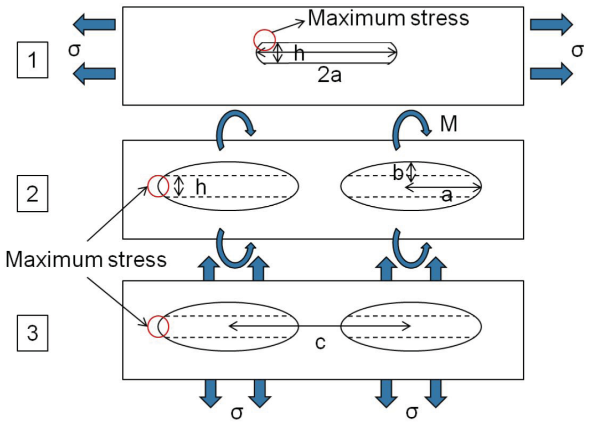


Figure 9: Schematic forces and moments of slotted plane [3]

Half circle-ends at each span-wise end avoided high tensile stresses in the corners of rectangle slots. In the literature this is referred to as an ovaloid [20]. It was found that it is necessary to account for the fact that the tangentially inclined jet has a distorted cross-section in comparison to the slot incorporated in the structure. This has to be considered, when using the jet area as a part of equation (1). The concept of the equivalent ellipses was found in [20] and implemented to check the influences of chord- and span wise lengths of the slot with an analytical parameter study. It was found that the main factor, determining the maximum slot stresses, is the distance between two slots. It became clear that the parameters affecting the aerodynamic jet performance and the structure are intervened. A narrow slot in chord-wise width will increase the slot stresses in the corners, while it will reduce the jet cross-section. For a constant momentum coefficient in equation (1) this yields to an increased jet velocity, which is limited by compressibility effects. More research has to be undertaken in order to find a satisfying optimum within structural as well as aerodynamic constraints.

### 7.3. Assessment of AFC-integrated structure

The obtained information was transferred into a more detailed FEM model with slots and a simple diagonal wall representing the actuator. Due to the additional pressure applied in the plenum, the stresses changed in comparison to the basic model. The area moment of inertia also changed, due to the actuator integration, but it was argued that the significance can be neglected for a first estimation. Initial high slot stresses were reduced by a reduction of the actuator plane thickness. To be consistent with the assembly concept, the slotted plane thickness was increased, which also reduced the stresses significantly. The critical region was found to be located close to the load introduction rib, which is due to the flap compression in this region. It was shown that the developed concept can cope with the static ultimate loads using aluminum as the preferred material. Additionally, it was proven that the force flux through the plenum boundary worked as intended. The fact that most of the slot stresses remained below the limit with an offset to the failure scenario, yields to the assumption that static structural integrity can be reached by locally optimizing the thickness of the structure. This short description of the structural assessment shall not be regarded as conclusive. However, it gave more confidence in the following points:

- With a structural design effort it is possible to incorporate slots into the structure with a reasonable effort.
- No issues were found with respect to the conceptual design of the integrated actuator
- A shape of the exhaust slot was defined and the span-wise interaction between the slot-stresses was pointed out to be the major stress source
- The general deformation pattern of the leading edge box in chord-wise and span-wise direction was better understood
- Improving the weight impact of the actuator

## 8. CONCEPTUAL SUPPLY SOLUTION

Three full-span flap pressurization concepts will be presented in the following. The flaps are thereby deployed by a track-based kinematic system on a non-circular route. In order to assess the supply integration into the flap track fairing, a three-dimensional CAD space allocation model was built from drawings.

### 8.1. Track-beam based pipe docking system

The most simplistic concept can be seen in Figure 10.

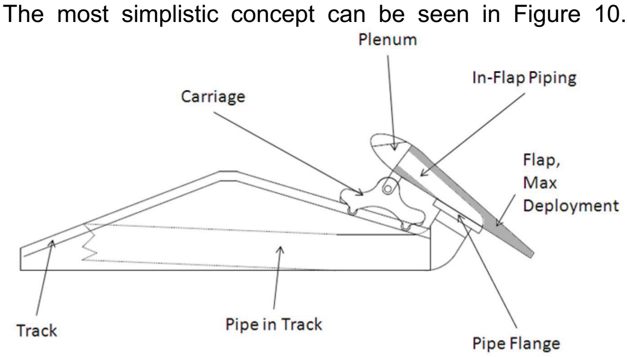


Figure 10: Track based pressure supply concept [3]

The pipe is guided between the webs of the flap track beam and ends with a flange. This flange is a spherical bearing adapter with a spring to assure constant contact to the flap at maximum deflection angle. The flap has a hole on the lower panel, coinciding with the pipe when the flap is fully deflected. The described docking station is connected to an internal flap duct, which pressurizes the plenum in the flap leading edge box. Except for the rotational bearing of the flange, this system has no moving parts and is very simple and easy to manufacture. The pressure loss associated is assumed to be minimal due to the single bend. From a kinematic and structural point of view the supply system is not endangering the deployment process. However, the pressurization of the flap in only one deployment position is limiting the envelope of the AFC system drastically. In the flap itself an additional ducting from the rear through the front spar is necessary, yielding to more stringent fail-safe precautions. Looking at operability, wear-out has to be addressed and maintenance will be required.

### 8.2. Folding pipe in fairing

The second track based concept is presented in Figure 11. By the using two hinges, three pipes are interconnected, following the same folding motion as the front linkage system. The pipes are positioned next to the links and a pressure delivery is again only possible for the maximum deployment angle. A sealing lip is incorporated into each pipe end, where it is attached to the next duct. This lip is self-sealing using the internal pressure of the duct. The advantages of such a system is the short duct and the fix connection to the pressure-plenum in the leading edge box of the flap.

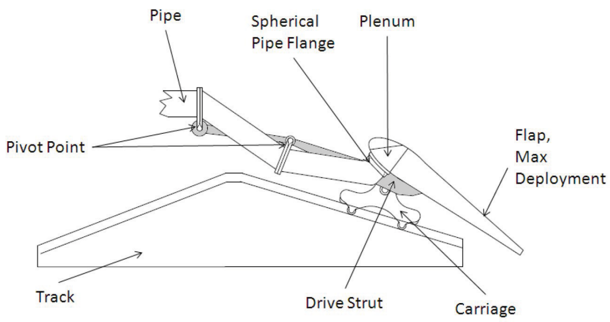


Figure 11: Foldable pipe for pressure supply [3]

However, large pipe diameters require a large amount of space, which yields to a lateral size increase of the flap track fairing, having a strongly detrimental effect on the aerodynamic cruise efficiency. Additionally, the possibility of jammed hinges has a strong impact on the redundancy of the flap kinematics. From an operability point of view leakage issues might occur at pipe interfaces when the seals deteriorate after being subjected to environmental conditions, which is the case when the flap is retracted.

### 8.3. Kink based telescopic pipe

The third concept is depicted in Figure 12. The delivery system is installed at the kink, and provided with pressure from the engine. No spoiler is installed at the kink, yielding to a relatively small amount of installments in the flap cove. Advantageously, the telescopic supply duct simultaneously delivers pressurized air into the leading edge box of the in- and out-board flaps for all settings. Figure 12 schematically shows that the setup is free to rotate about the span- and cord-wise direction, being the Y and X Axis, respectively. By adding a flexible gimbal joint about the vertical axis all three rotational degrees of freedom are covered. The combination of translation in the telescopic joints superimposed by the rotation also allows a movement in the three translational directions. The pipe ends form a spherical bearing, which is incorporated into a redesigned end rib. An additional telescopic joint, connected to one of the bearings, uncouples the individual span-wise movements of the flaps. The legacy high lift system has an interconnection strut between the in- and outboard flap, stiffened by hydraulic pressure in case of a flap actuation failure. Systematic synergies with the supply system are therefore existent. The fact that only one delivery system is required for the whole wing, results in a minimum weight and complexity impact, but also requires the system to be fail safe. Looking at cruise impacts it is expected that no extra fairing is necessary, while it is still accessible for maintenance purposes. The pipe diameter is twice the size compared to the first two concepts, since the whole mass-flux for one wing has to be delivered through one pipe.

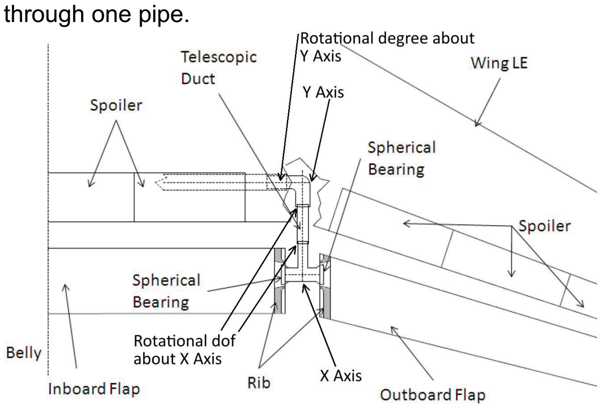


Figure 12: Kink based pressure supply for inboard and outboard flap [3]

## 9. PRESSURE SUPPLY

AFC mass-flow quantities, which were calculated to be in the order of 4.55 kg/s, can only be delivered by a modified propulsion bleed air system. For this case deicing has to be managed by means of other sources, such as electricity and the air conditioning has to be turned off for the final approach. The fan air with following characteristic, was found to be an interesting candidate in order to provide the AFC system with relatively low pressures and high mass-flow rates.

- Large mass-flux quantities
- Low temperatures behind the first fan air stage
- Low pressure differences

A fan air bleed valve, which extracts fan air to cool down the high pressure and high temperature bleed air from the engine core, was assumed to be usable for an extraction of pressurized fan air. A program was developed, which is able to determine all aerodynamic flow properties with respect to the preliminary aspect of this study. Literature [21][22][23][24][25][26] was used to derive a method, which is capable of predicting the pipe pressure losses in the telescopic supply. The properties were calculated with a set of compressible adiabatic flow equations, which are mainly solved iteratively. Accounting for bends, valves and other flow obstacles, empirical flow resistance values were included. For a given flight scenario, mainly represented by atmospheric conditions and flight velocity, the necessary plenum conditions were derived according to the extrapolation of test results for a fluidic actuator given by Bauer (TU Berlin). In an iterative manner the fan pressure ratio of the engine was adjusted in order to account for the required total pressure difference as well as the associated predicted pressure losses in the telescopic ducting. For normal approach conditions this resulted in values of about 80% of the maximum assumed fan pressure ratio. However, at this time no link could be made to the associated thrust of the engine, which is usually very low in approach conditions. Therefore, more detailed studies have to focus on the fan air extraction with respect to thrust settings and the linked flight performance. The pressure loss is mainly depending on the applied total inlet pressure. This again is a result of the required plenum pressure. The highest pressure loss occurs for the fastest flight velocity. The pressure drop increases with respect to the flight velocity and behaves similar to the total plenum pressure increase. The high velocity causes large frictional losses, which increases the pipe exit Mach number. The interconnection of plenum pressure and pressure loss can be also seen in the result of the altitude variation. A climb to about 3000 ft altitude reduces the pressure requirements as well as the associated pressure losses about 9%. A stronger effect is caused by the temperature increase of 80 K, which yields to a pressure loss reduction of 21.7%. This is mainly driven by the required plenum pressure reduction. The opposite effect occurs when the ground pressure is raised by 24%, causing a pressure loss increase of about 23%. Since the actuator efficiency is linked to the dynamic pressure of the jet, a better performing actuator yields to lower plenum pressures and lower pipe inlet pressures. During the pipe diameter evaluation it was proven that a duct diameter reduction increases the pressure loss rapidly.

## 10. WEIGHT IMPACT

In the following the weight increase will be described. The weight was classified into two separate components: Additional weight of structures located in the inboard flap and weight associated with the pressure supply devices. In total the estimation yields to a flap structure weight increase, which represents about 30 percent of the total FNG flap weight. As indicated above, the pressure supply weight has to be separated from the internal flap structure weight increase. This is due to the location, but also the error is assumed to be higher since the flap actuator design is far more advanced. Aluminum was chosen and it was assessed that the total pressure delivery system weighs 35 kg. This section is assessing the weight in an early conceptual stage and it is believed that the weight can be significantly reduced. Additionally, no benefits have been accounted for. That is, successful separation elimination could reduce the flap size and weight or even make it possible to use much lighter and simpler kinematic systems.

## 11. CONCLUSION

A wind tunnel test campaign in collaboration with the Technische Universität Berlin concludes that the active flow control test on the industrial 3D high-lift half-model successfully increased the lift by eliminating separations. Due to large pressure losses and long and small pipes the signal of the jet was deteriorated and compressibility effects most likely limited the jet momentum. It can be assumed that the current lift coefficients can be exceeded in a flight scale environment. The best relative efficiency value of about 0.2% $C_\mu$ was used for a subsequent white paper study on the generic aircraft FNG. It was possible to integrate a fluidic actuator concept, while taking manufacturing and assembly constraints into account. After defining an ovaloid slot shape it was explained that the spanwise distance between the slots has a major influence on the slot stresses. It can be concluded that slot stresses are manageable with some dedicated design work. The kink-based pressure supply system was favored over track based concepts with multiple supply stations, complex mechanisms, associated fairing increases and an AFC system, which only is only useable for fully deflected flaps. The fan air as a pressure source was argued to provide the required characteristics. However, the associated thrust level was not accounted for, raising the need for further bleed air design work. The methodology of the internal flow performance evaluation was briefly described. Concluding with the significant weight increase, it has to be outlined that especially for full-span applications of this technology only a trade at overall aircraft level could show that a positive benefit can be achieved. Giving an outlook, from the authors point of view the aerodynamic research has shown that especially pneumatic pulsed blowing active flow control is able to eliminate separations and therefore works as intended. However, much more work has to be done on a global aircraft level in order to address more dominant challenges. Redundancy issues, caused by bleed air and engine malfunctioning can not be neglected. Past and current research shows that the aerodynamic feasibility is high, therefore parallel to further analysis and research, supplementary industrial assessments have to be made focusing on the optimal use of this promising technology.

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