4.1 Final publishable summary report

Executive summary

Active flow control by means of pulsed blowing has proven to be effective and efficient to delay or avoid flow separation on aerodynamic bodies and therefore increases their operating range. Such active flow control systems, however, require effective, efficient, and reliable flow control actuators, the design and validation of which was the aim of the project DT-FA-AFC. Different flow control actuator concepts have been the focus of research in the past decades. The variety ranges from piezo-driven Zero-Net-Mass-Flux (ZNMF) actuators, plasma based actuators, and mechanical valves to pyrotechnic actuator and moving pistons. The control authority and frequency range of those actuators vary greatly, all have their pros and cons, and all concepts were tested more or less extensively in lab scale experiments. Only very few concepts reached the maturity level to be flight tested and no concept was ever considered for commercial (civil) application.

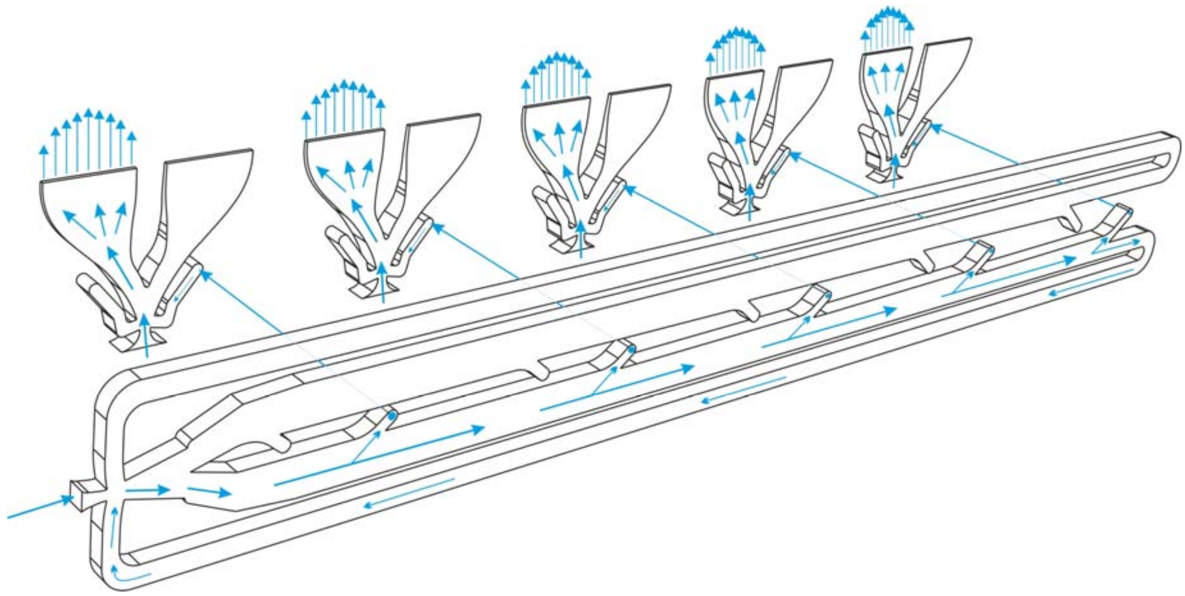


figure 1: principle of staged flueric actuator system

Within the frame of DT-FA-AFC it was attempted to develop a core flow control actuator system that has the potential to be considered for commercial, civil application. In the course of the project an aircraft scale fluidic actuator system was devised that produces high amplitude pulsed air jets without incorporating any moving or electrical components (see figure 1). The system performance was evaluated (in close cooperation with SFWA project FloCoSys) in bench-top experiments. Its design was provided to SFWA project AFCIN to study the integrability into a trailing edge flap modified for AFC application. The combined findings of DT-FA-AFC, FloCoSys, and AFCIN show that it is possible to design an actuator system for active flow control that is capable of providing the necessary control authority in a relevant frequency range, while being sufficiently robust und compact to be considered for integration in a civil airliner.

Summary description of project context and objectives

As an aircraft spends most of its flight time in cruise its wings are optimized for that part of the mission. Nevertheless, during take-off and landing, the wing needs to provide sufficient lift at low speed and therefore requires a high-lift system, which is usually a complex combination of leading and trailing edge flaps. These components increase complexity and weight of the overall system and therefore increase the direct operating costs and fuel consumption. Active flow control on those devices enables the design of systems of less weight, less complexity, or simply smaller elements. Such active flow control systems, however, require effective, efficient, and reliable flow control actuators. The design and validation of which was the aim of SFWA project DT-FA-AFC.

First a single element fluidic actuator was designed in close cooperation with Airbus and the SFWA partner projects FloCoSys and AFCIN. An actuator shape was found (using CFD tools) which fulfils the AFC parameter requirements specified by Airbus and fits into the relevant civil aircraft trailing edge flap. In addition, steps were taken to derive a driving system for the output stage actuator elements and to implement the single elements into a larger array of actuators.

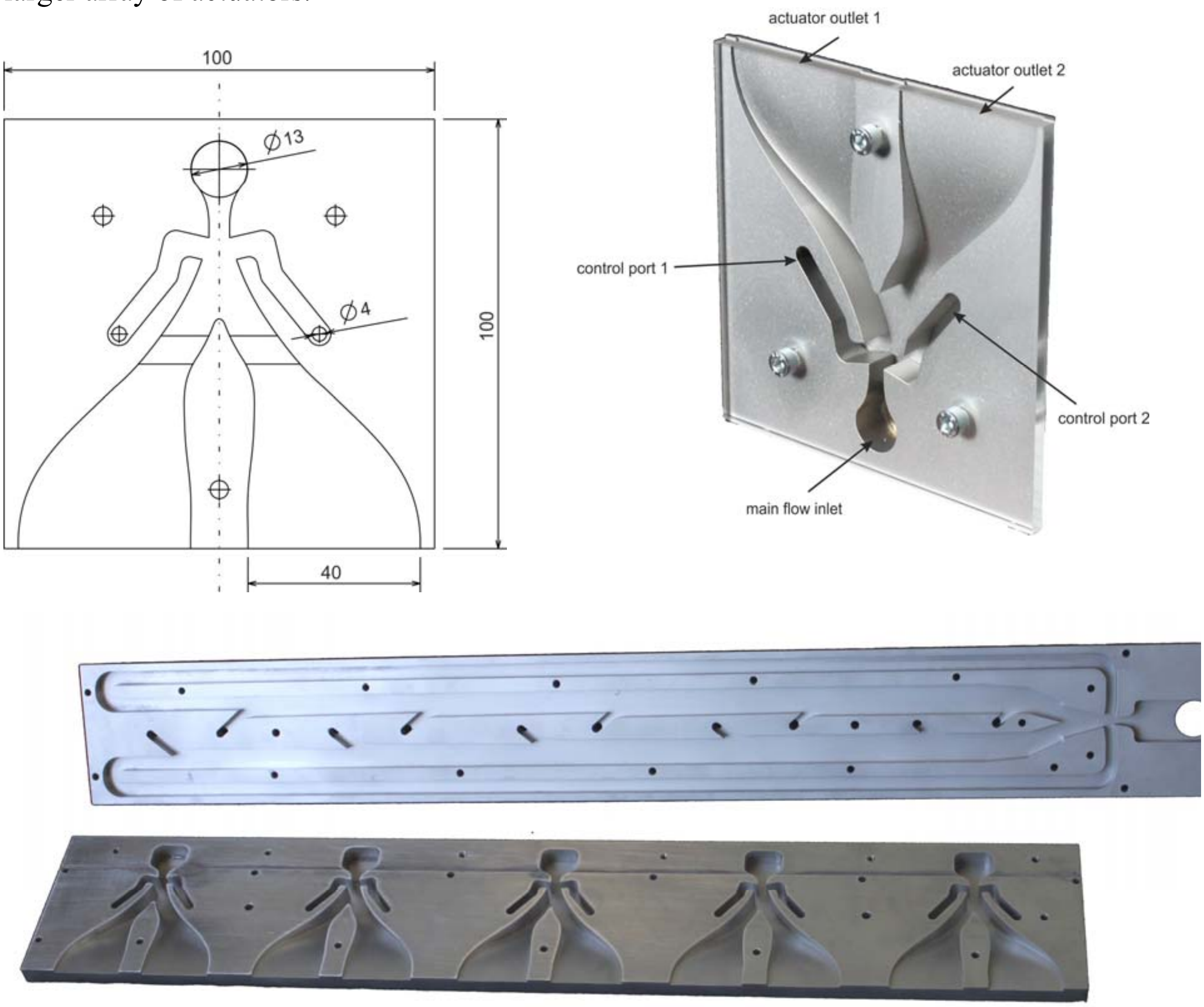


figure 2: single actuator element in CAD, machined from aluminium and integrated into an array (with driving stage in background)

After having arrived at a satisfying shaping for an individual outlet stage actuator element, the integration of those elements into an overall actuator system was worked on. The efforts comprised the manufacturing and testing of prototypes, the design of a driving stage, and the downscaling of the aircraft scale actuators to wind tunnel model scale. The testing and evaluation process consisted of two stages. First the performance of ONE single element of the outlet stage was evaluated. It was found that at a frequency of 150Hz the actuator is fully modulated at the design point. There is also sufficient margin to low performance especially with respect to undersupply of control mass flow (see figure 3**Fehler! Verweisquelle konnte nicht gefunden werden.**).

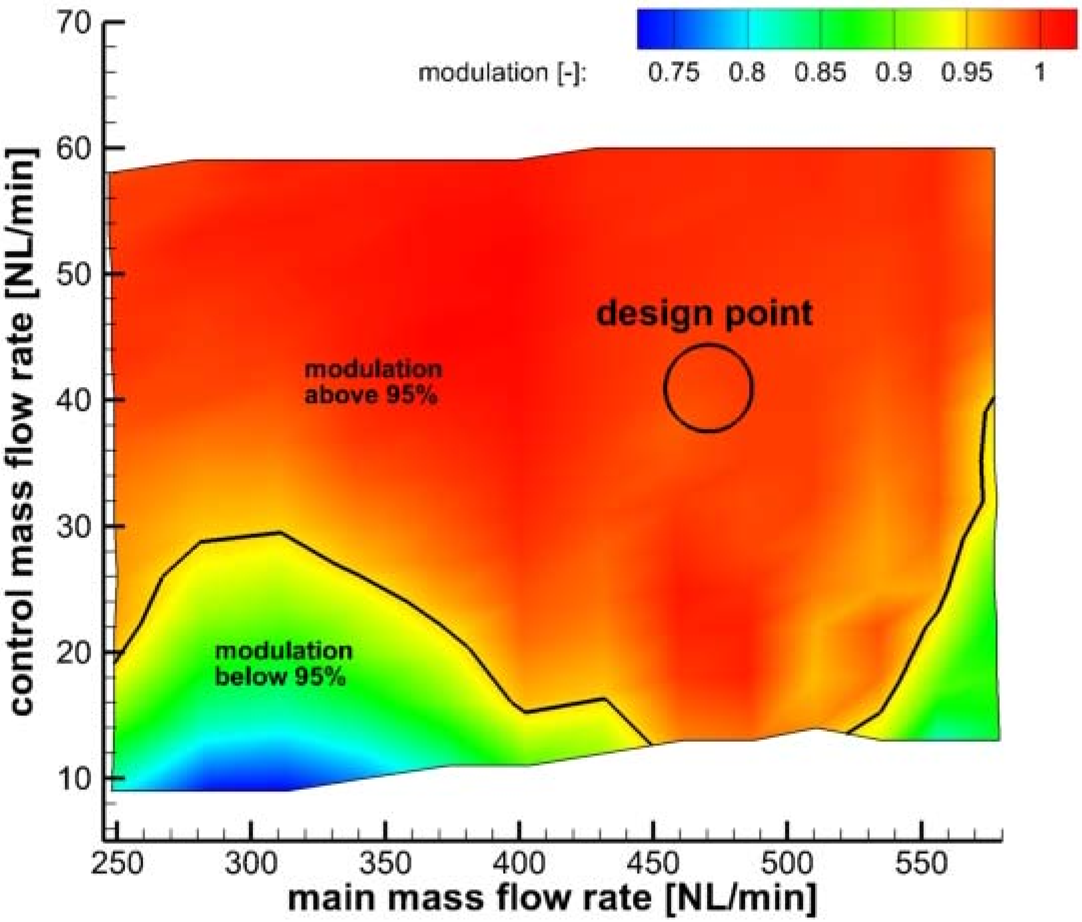
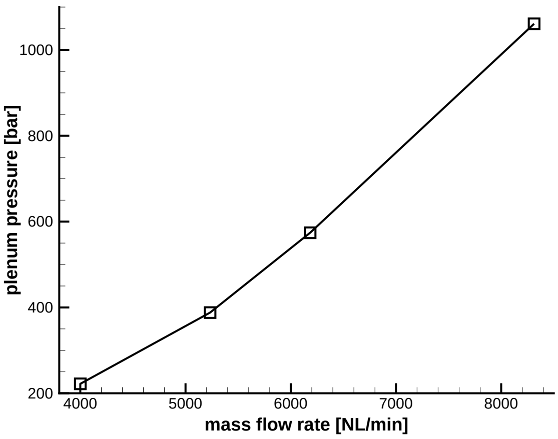


figure 3: modulation for 150Hz actuator operation

The second stage focused on the testing of the flueric actuator array. This AFC system consists of a plenum, a driving stage, and an outlet stage. Only driving stage and outlet stage are considered to be the core actuator system. Both stages are supplied with the same pressure level through the plenum. The design point for the flueric actuator array is at an inlet pressure level of 500mbar above ambient. As a result of employing only one pressure level for both stages, the frequency is a function of the pressure in the plenum - and therefore the mass flow rate. (see figure 4)



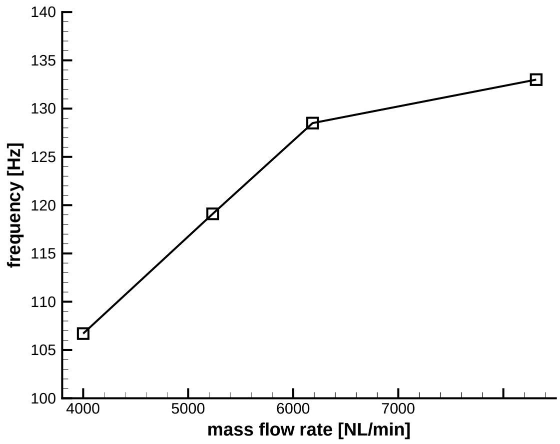


figure 4: correlation of plenum pressure and mass flow rate (left) and frequency and mass flow rate (right)

For the flueric actuator array the total pressure of the air jets was measured at the outlets relative to ambient pressure. The velocity distribution along the actuators' span of 600mm is sufficiently even and the actuators output is fully modulated for all tested pressure levels applied at the plenum (see figure 5).

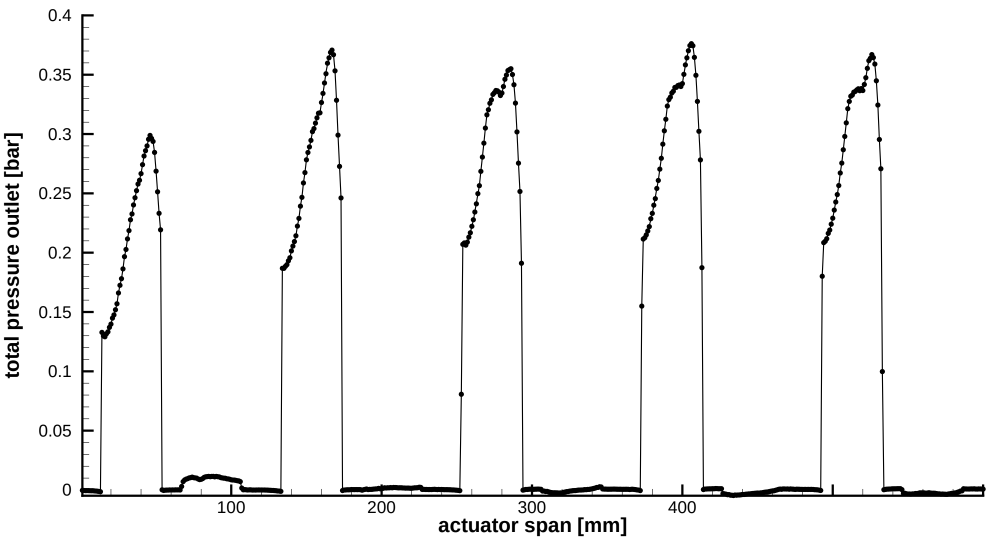


figure 5: total pressure of air jets generated by flueric actuator array

In addition to design of a flow control system at aircraft scale, this design was downscaled to wind tunnel model level (see figure 6). Here two different pressure levels were applied to driving and outlet stage to allow for setting the a frequency independent of the actuation amplitude (within limits). Extensive pressure measurements proved the functionality of the downscaled actuator. Analogous to the large scale actuator, modulation was considered to be the parameter to qualify the actuators' operability. For main flow rates greater than approximately 2000NL/min/meter, the actuator shows a modulation of more than 90% for all tested parameter combinations. The achievable frequency ranges from 170Hz to 240Hz.

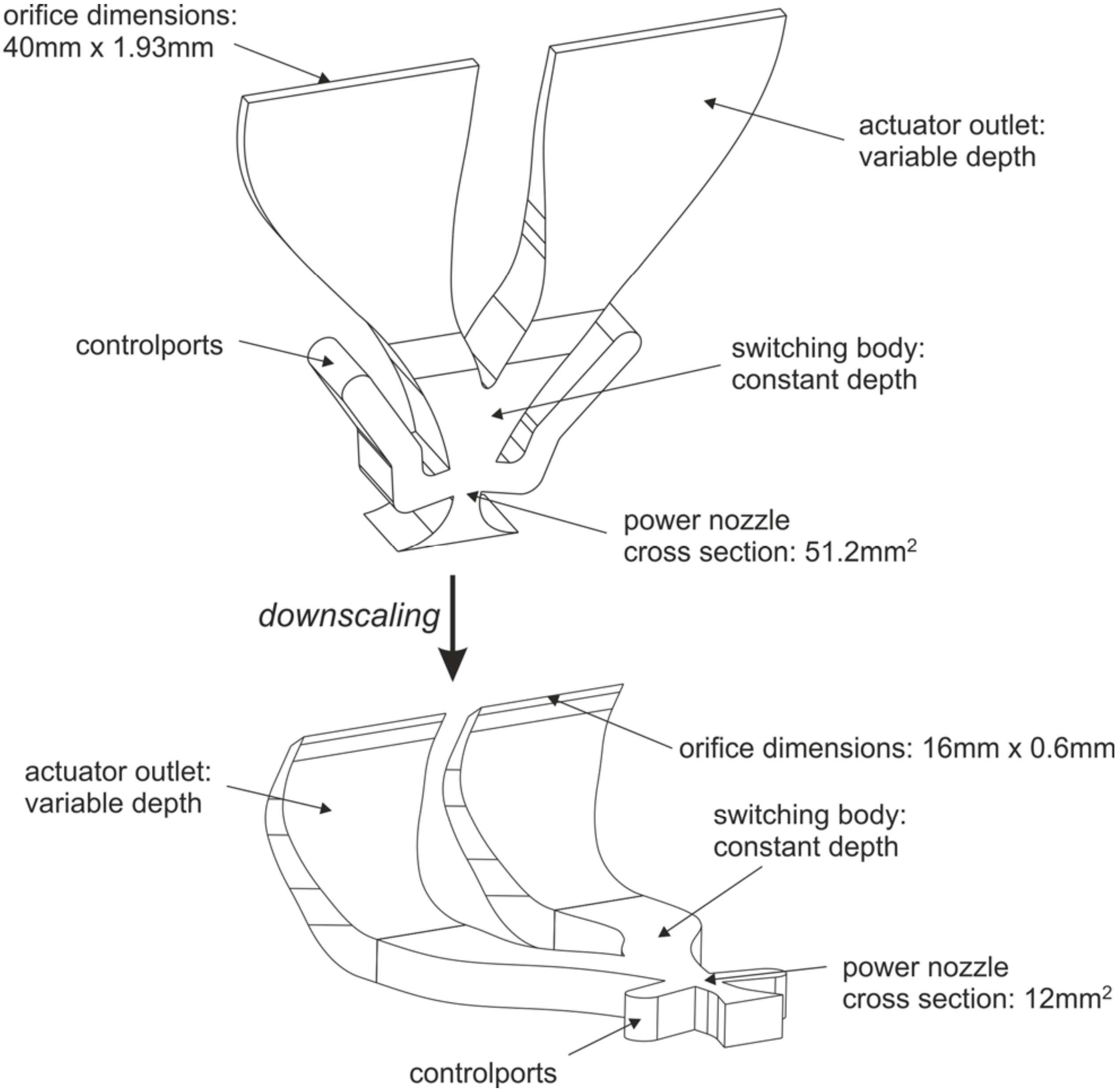


figure 6: comparison of a/c scale and w/t scale actuator element (not to scale)

Therefore, in the course of the project, significant progress was made with respect to flow control hardware development. Starting from industry requirements and a technology concept a robust and efficient flow control actuator system was designed, optimized, and tested. It was proven in bench top experiments that it is possible to design an AFC system that has sufficient control authority to be implemented at aircraft scale. In addition, the project provided input to partner projects FloCoSys, AFCIN, and the ongoing SFWA project robustAFC.

Description of the main S&T results

The main results are presented along the lines of work packages and given in form of a summarized version of the deliverables.

WP1

Abstract

In WP1 a specific fluidic valve is proposed as a starting point for further optimization. The decision is based on input provided for SFWA projects in “Reference Aircraft Definition” by Lengers/Scholz (Airbus). Based on this input the sizing and required output in terms of jet velocity of a single element actuator are estimated.

The proposed actuator is a curved wall type fluidic diverter with a straight actuator chamber mounted at the outlet of the interaction zone. It’s initial working point is defined by a mean output velocity of 100m/s, a frequency of 100Hz and a momentum coefficient of 0.11% in accordance with the requirements for the model aircraft.

AFC system requirements provided in “Reference Aircraft Definition”

The document “Reference Aircraft Definition” [Lengers/Scholz (Airbus)] provides requirements for an AFC system, which allows the reduction of size of the trailing edge device due to increased lift on a highly inclined single slotted flap without affecting the performance of the overall aircraft.

The additional lift to be provided by an AFC system is 11 lift counts. It is estimated that a momentum coefficient of $c_\mu = 0.11\%$ is required, if the AFC system employs pulsed blowing. This estimate is based on HIREX experimental and numerical data.

The velocity of the oncoming flow is given with 60m/s.

As the reference aircraft’s flaps are tapered, required actuation frequencies (between approx. 50Hz and 300Hz) and available installation space vary with spanwise location. However, as starting point one actuator geometry is defined at midspan. Geometries for other locations are derived by scaling this actuator.

Parameters for single actuator element

Infinite combinations of the parameters "outlet slot geometry" and "jet velocity" can fulfill the requirements, therefore some of these have to be chosen based on experience and general considerations.

a) Mean jet velocity: From functional principle, the duty cycle of a fluidic actuator is fixed at DC=0.5. Therefore the peak jet velocity is approximately double the mean jet velocity. From previous experiments it known that the velocity ratio of $u_{jet,mean}/u_\infty$ must be larger than unity. The minimum mean jet velocity is therefore 60m/s. The maximum peak exit velocity is limited by the requirement of the jet to be subsonic. Therefore the maximum mean jet velocity is approx. 150m/s. To allow for sufficient distance from each of these limiting velocities, the design mean exit velocity is proposed to be 100m/s.

b) From the work of Höll (referenced in “Reference Aircraft Definition”), the most promising ratio(a/c) is found to be in the range between 0.62 and 0.76. As starting point for the actuator design process the upper limit provided is chosen for two reasons:

- Low ratio(a/c) infer low ratio(a/h) (here: approx. O(10^1)) while most experimental data exists for higher ratio(a/h) (O(10^2))

- Decreasing ratio(a/c) is possible without changing the actuator element spacing, while the opposite is not true.

c) The slot length is chosen to be 50mm. (arbitrary)

With these parameters fixed the last remaining parameter slot width (h) can be calculated.

$$h = \frac{c_\mu \cdot q_\infty \cdot A_{ref}}{\bar{u}_{jet}^{\,2} \cdot \rho \cdot \left(\frac{a}{c}\right) \cdot span} \approx 1.5 \cdot 10^{-3}\, m = 1.5 mm$$

WP2

Abstract

The work performed in WP2 "Numerical Design and Simulation" aims at providing numerical data of the internal flow structure of a fluidic diverter actuator in order to select the most promising internal geometry for further development.

The proposed actuator from WP01 is a curved wall type fluidic diverter with a straight actuator chamber mounted at the outlet of the interaction zone. It’s initial operating point is defined by a mean output velocity of 100m/s, a frequency of 100Hz and a momentum coefficient of 0.1% in accordance with the requirements for the model aircraft. The working frequency was later changed to 150Hz.

Several iterative steps were taken - adapting the fluidic valve to changing available installation space and span where AFC is implemented - to arrive at a single element fluidic actuator which fulfills the requirements and fits on the flap. The resulting actuator design is displayed in figure 8.

Two possible operating points are proposed as a result of this WP:

- total pressure (at inlet) of 435mbar (above ambient pressure), a massflow rate of 3.9 kg/sec and equidistantly spaced actuator orifices

or

- total pressure of 490mbar (above ambient pressure), a massflow rate of 3.72 kg/sec and non-equidistantly spaced actuator.

Initial geometry definition

As the final step of WP01 an initial definition of the actuator geometry was provided to serve as a starting point for the numerical study. This initial geometry is in figure 7.

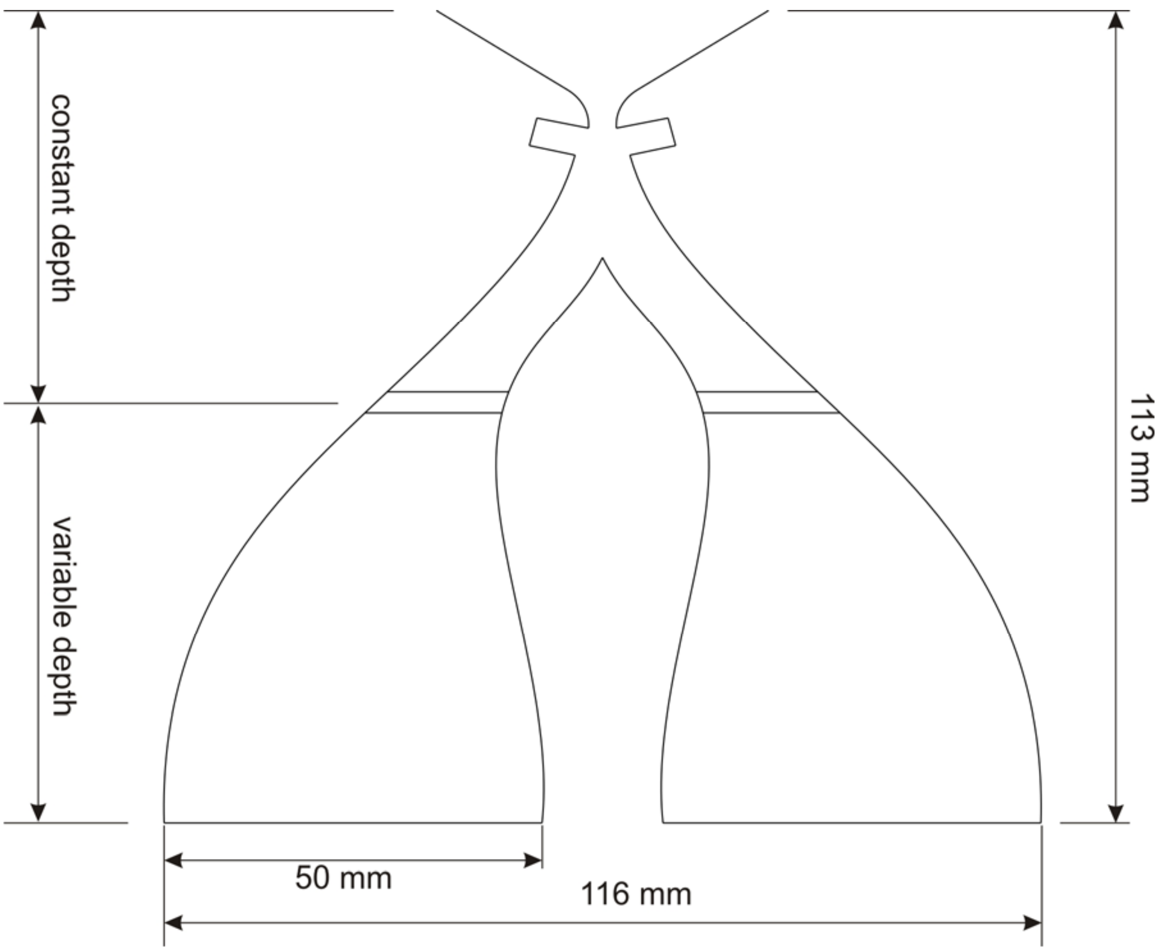


figure 7 Sketch of fluidic actuator including actuator chamber (not to scale)

As the relevant (and limiting in terms of integration) length of the actuator is its height, several iterative steps were taken (100mm height, 60mm height, 80mm height) to arrive at the final actuator shape. This is referred to as the K4.x family.

80mm Actuator - K4.x

Work in the JTI-SFWA project AFCIN has shown that the proposed reduction of the flap size to 60% of its initial size is not feasible as the expected aerodynamic loading would require an excessively increased flap skin thickness and therefore result in a disproportionately heavy structure and small installation space for the AFC system. Therefore it was decided to reduce the flap size to only 70% of its initial value. To keep the provided total lift constant the flap span was reduced. Therefore the local momentum coefficient requirements changed which again required a redesign of the fluidic actuator element.

figure 8 shows different views of the resulting design for a single fluidic actuator element. The bounding box of this actuator is 93mm x 80mm x 11mm. The sizing of the outlets is 2 * 40mm x 1.93mm.

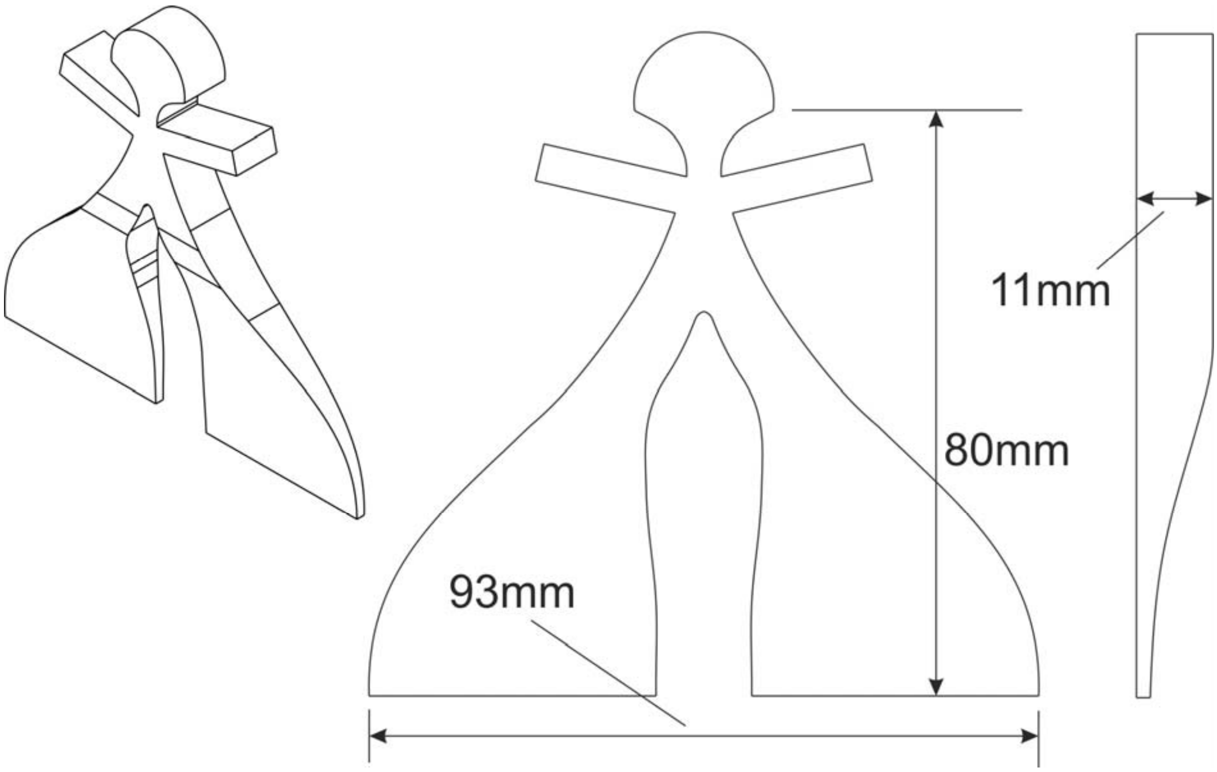


figure 8: drawing of the final actuator design from numeric simulation

For the numeric simulations the commercial flow solver Ansys CFX was employed. The grid is shown in figure 9. It consists of a total of approx. 2 million cells. The large outlet plenum adjacent to the actuator (consisting of another 2 million cells) is not displayed here. It is necessary to allow for the static pressure in the jet to equalize with the static pressure of the ambient region. The interior of the actuator is modelled using 7 blocks with fully non matching block interfaces. The baseline Reynolds stress turbulence model - implemented in CFX - was used for the computations, as it is best suited to predict pressure induced flow separation. For boundary conditions the total pressure at the inlet and static pressure at the outlet plenum was chosen. Convergence criterion was set to 10^{-5}. The shown simulation results are steady state.

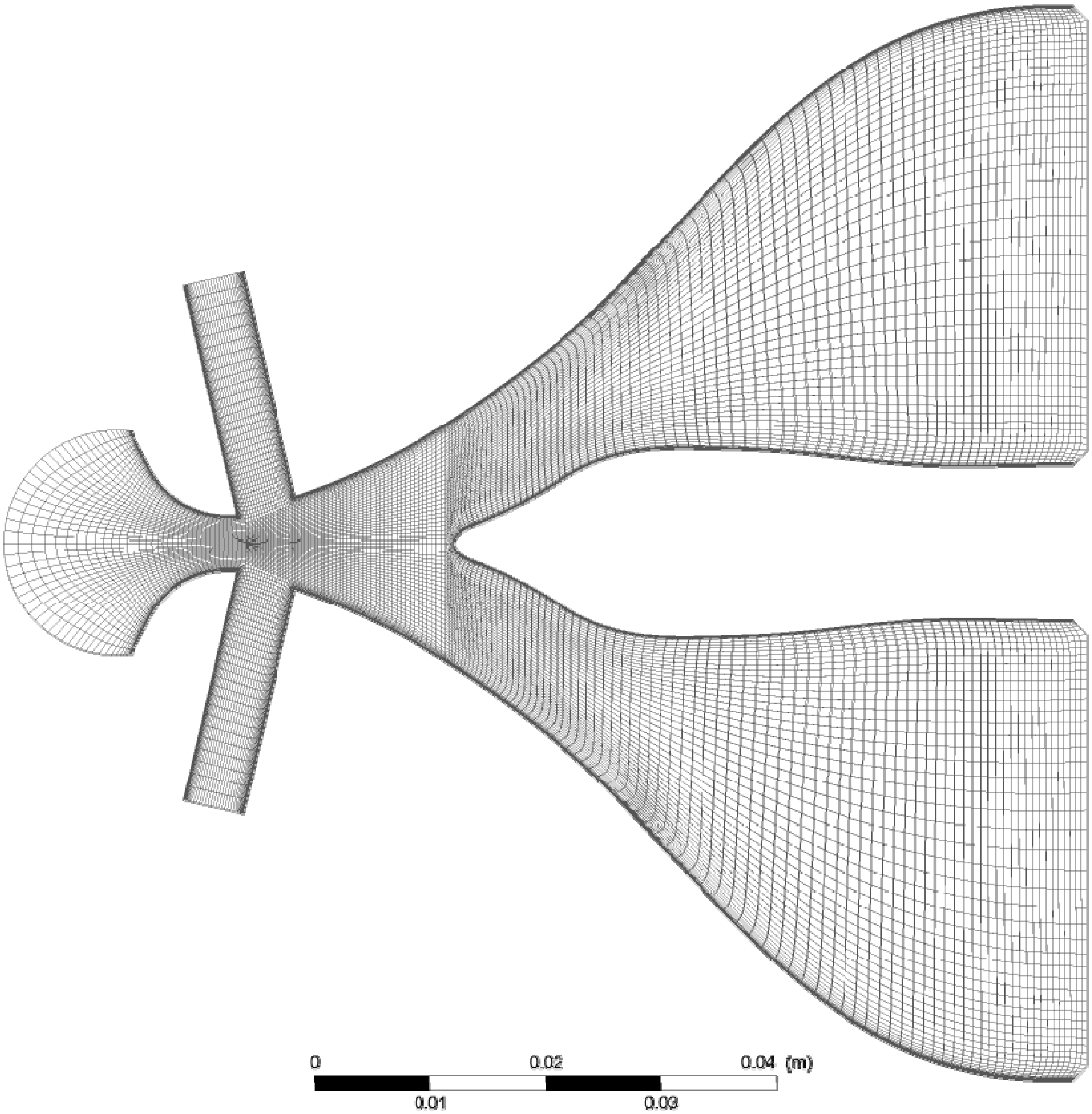


figure 9: Employed (final) mesh for the actuators K4.1 to K4.5

Two exemplary results of this simulation are shown in figure 10 (total pressure in mid plane) and figure 11 (velocity in mid plane). Both figures show results for the simulation case of approx. 500mbar pressure at the inlet and a inlet fluid temperature of 273.15 K. The existence of negative pressure in the domain is due to the fact that the reference pressure was set to 0 Pa.

Within the actuator flow separation occurs at the outside wall at approx. 50% of the wall's length, where the flow channel starts to contract (in direction normal to paper plane, see figure 8). Separation at this location is desired and necessary to allow for a sufficiently high switching frequency and to have a sufficiently even velocity distribution (in spanwise direction) of the jet exiting the actuator. A corresponding velocity distribution for the active actuator chamber is displayed in figure 12.

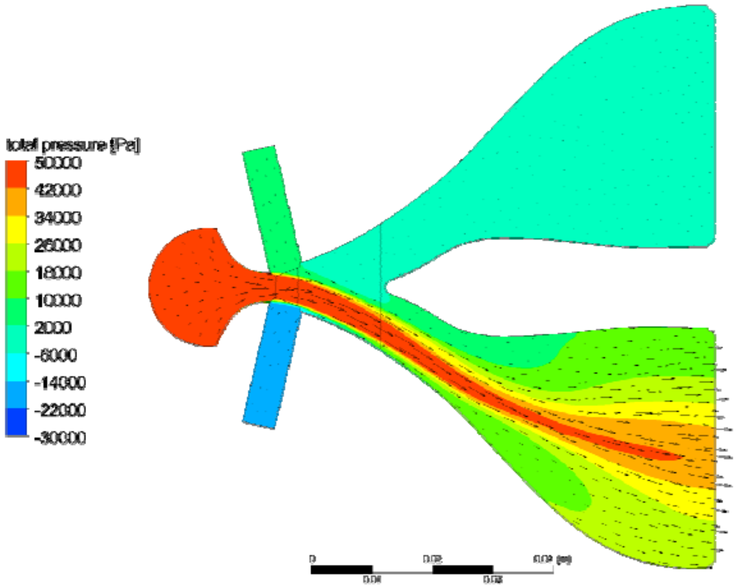


figure 10: contour plot of total pressure

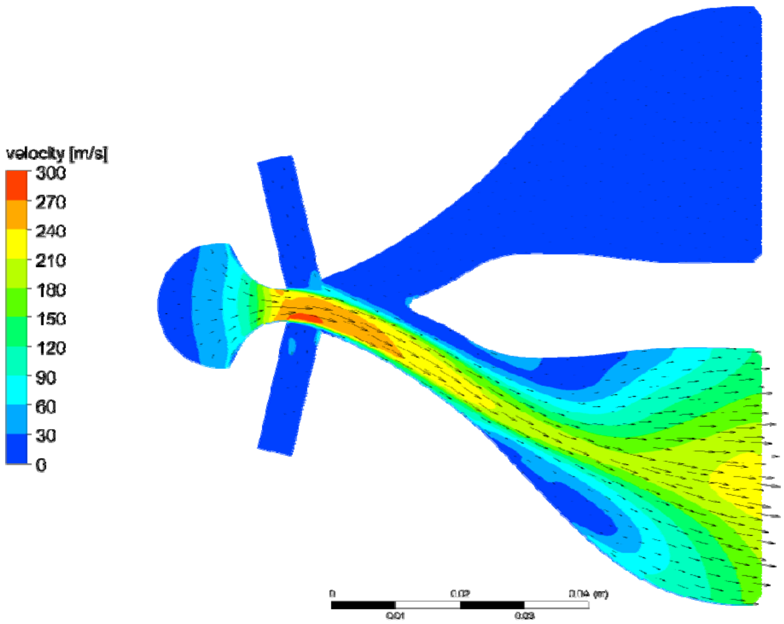


figure 11: contour plot of velocity

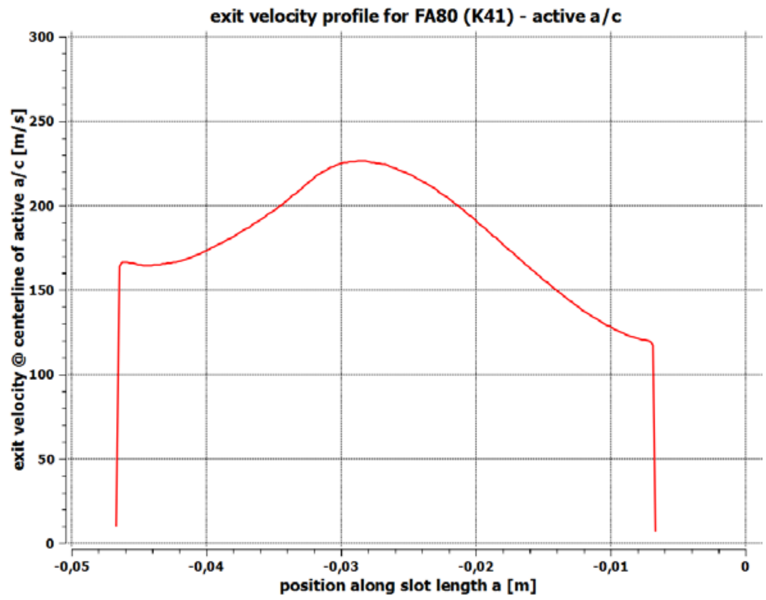


figure 12: exit velocity profile corresponding to contour plots above

A number of simulations with different inlet boundary conditions were performed to find the correlation between total pressure at the inlet and momentum coefficients calculated based on the reference aircraft data. Based on the results two different operating points are proposed to the partner projects. The required momentum coefficient can be realized with two different operating points: Either a total pressure (at inlet) of 435mbar (above ambient pressure), a massflow rate of 3.9 kg/sec and equidistantly spaced actuator orifices or a total pressure of 490mbar (above ambient pressure), a massflow rate of 3.72 kg/sec and non-equidistantly spaced actuator orifices.

For the non-equidistantly spaced actuator outlets, the distance between the two outlets of any one actuator element would be half the distance (g1 ~ 13mm) of the distance of two neighbouring outlets (g2 ~ 26mm) of any given two neighbouring actuator elements (see figure 13).

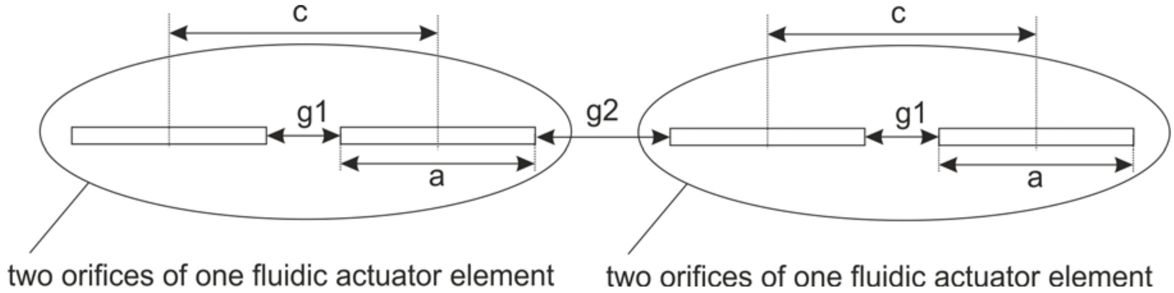


figure 13: outlet distribution for non-equidistantly spaced orifices

Conclusions

The actuator K4.1 is chosen as input for the following work packages.

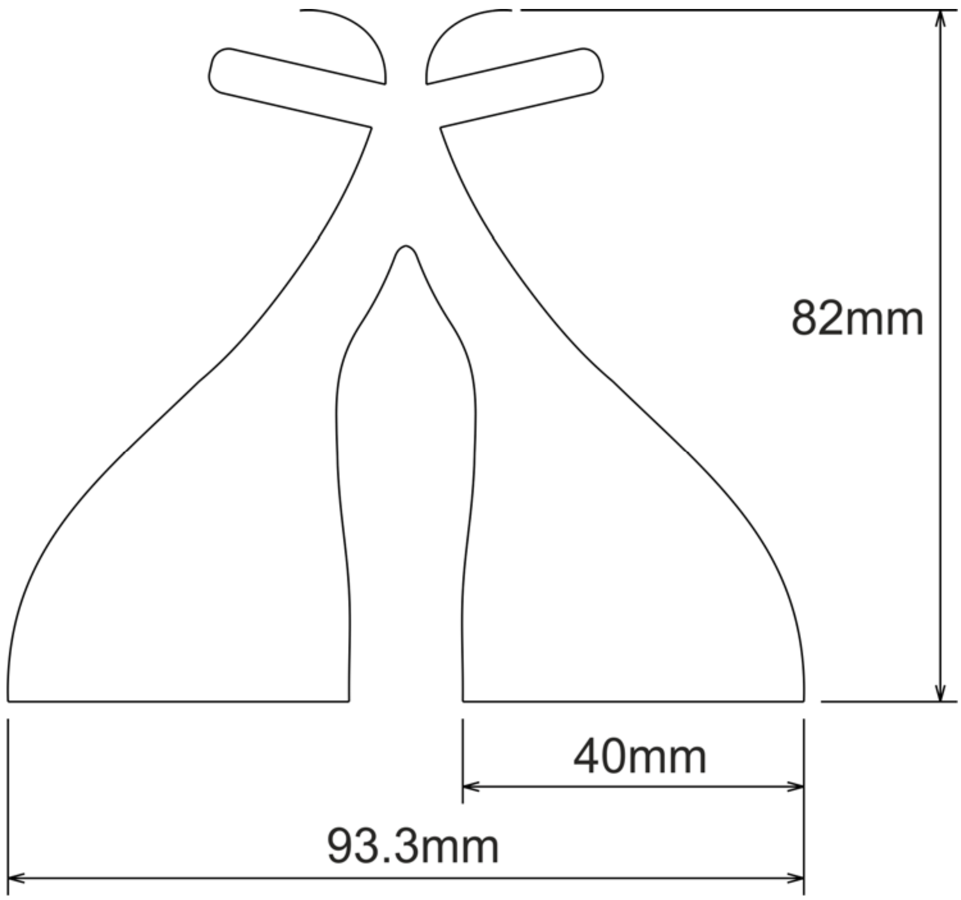


figure 14: actuator as input for following WPs

Based on discussion with project partners the operating point:

- $p_{t,inlet}$ = 490mbar
- m_{AFC} = 3.72 kg/seg
- g1 = 13mm; g2 = 26mm

is chosen, as the resulting total pressure losses are expected to be lower for this operating point.

WP3

Abstract

Based on the analysis of the numeric data generated in WP2 and accompanied by prototype hardware testing, the design of a single element fluidic actuator was completed and the element was integrated into an array of actuators.

Based on this design a single element actuator was derived that could be manufactured and equipped with sensors and supplied with pressurized air. For testing the single element a plenum (settling chamber) was added to the fluidic actuator body. This allows meassuring static pressure in the plenum and treating it as total pressure, due to the fact that the flow velocity is very low there.

In figure 15 the different elements of the design are shown. The inflow of pressurized air is realized by tubing from the sides. A screen is employed to reduce turbulence and to increase the homogeneity of the flow, before it enters the actual actuator element. For the element the power nozzle shape was modified to avoid separation in the intersection between the plenum and the actuator element. The contraction ratio from plenum to nozzle is 40:1. For testing, this single element was driven using a FESTO solenoid valve of type MHP2-MS1H-3/2G-M5. This valve allows for volume flow rates of up to 100NL/min (FESTO specification) and frequencies of up to 330Hz.

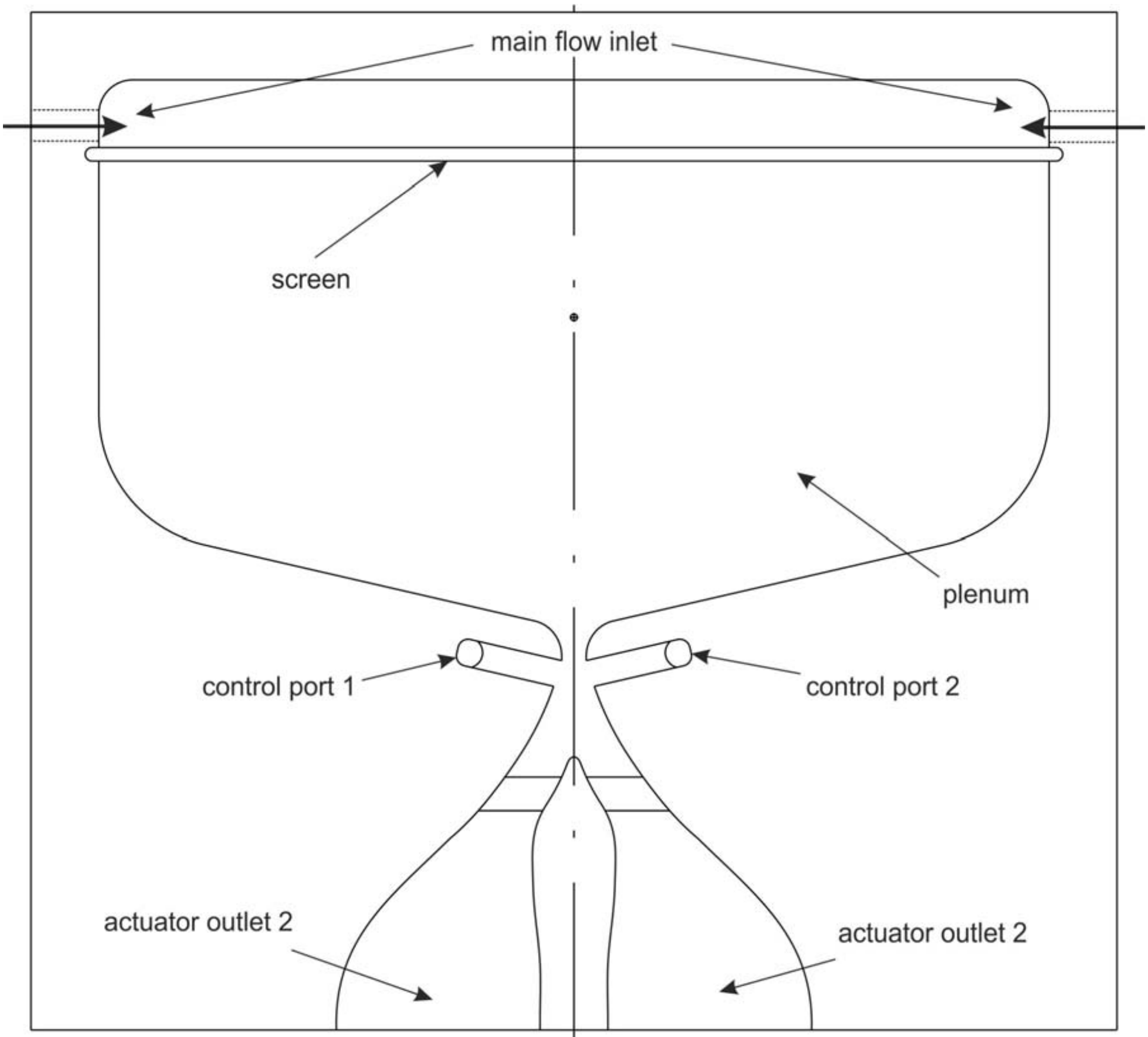


figure 15: schematic of tested single element

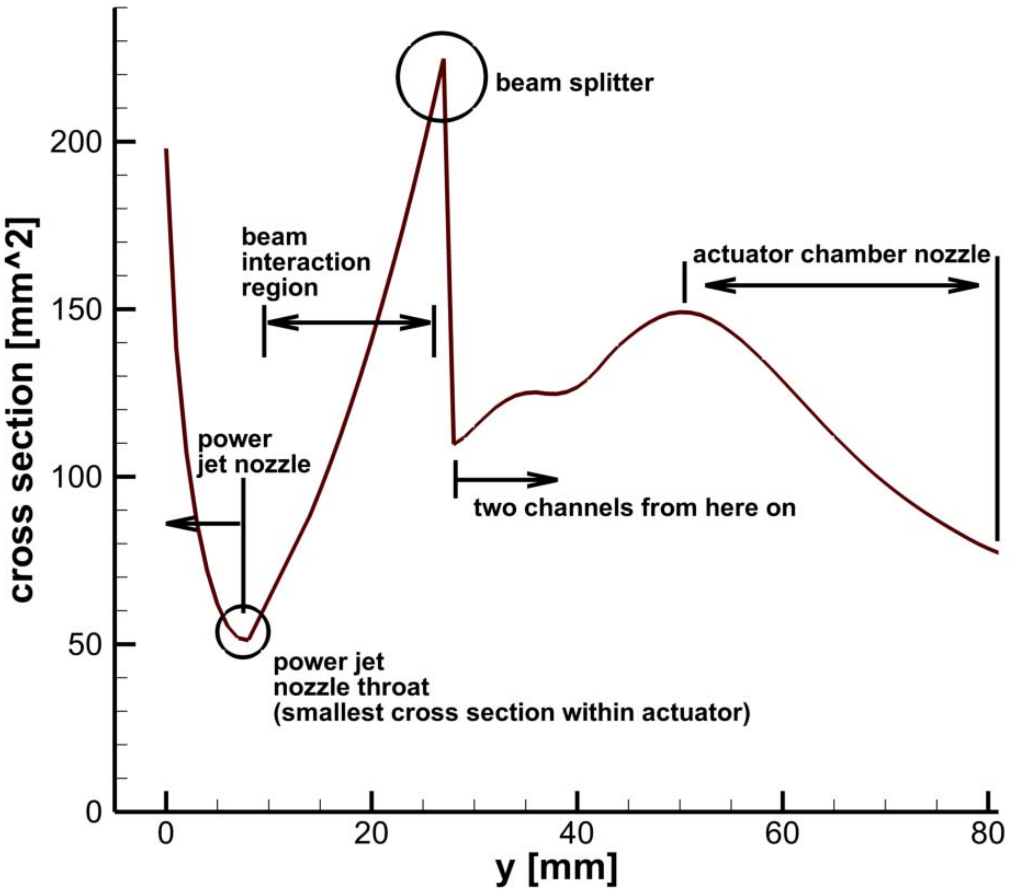


figure 16: cross section along fluidic actuator element

The variation of the cross section of the internal fluidic actuator geometry is displayed in figure 16. From principle, the actuator is divided into four regions. The air enters the actuator from the plenum and is accelerated through the power jet nozzle. It then enters the interaction region trailing the power jet nozzle. Here, the jet is deflected by the control jets and enters one of the two channels trailing the interaction zone. This region, where the cross section increases, is the receiver of the jet and channels the flow to the actuator chamber, where the flow is again accelerated and homogenized in spanwise direction. The jet then exits the actuator through a slot into the surrounding flow. Over the actuator (from power jet nozzle to outlet) the cross section changes from 4.8mm x 10.66mm to 40mm x 1.93mm.

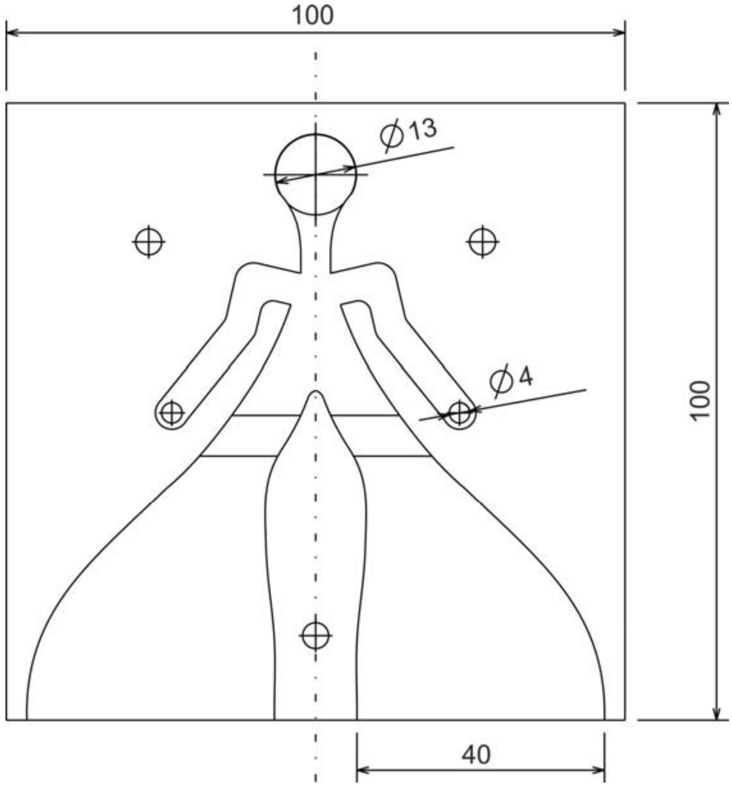


figure 17: CAD drawing of single element fluidic actuator

Above the CAD drawing of the single element fluidic actuator is displayed. Testing of the element suggested that some changes to the design might prove beneficial. The receiver height was increased and the attachment wall curvature was increased to force earlier flow separation and therefore decreasing the switching time. This was necessary to compensate for the increased length of the actuator, which was agreed upon during the course of WP2.
some relevant changes are therefore:

- change of the pressure supply routing - this enables easy integration into the flap and stacking of driving stage and outlet stage
- as mentioned: attachment wall curvature
- as mentioned: receiver height - increases modulation
- routing for control port inflow modified - necessary for later mounting of control stage

Single element integration - fluidic actuator array

As described in the initial proposal a cascaded actuator system was developed within the course of this project. It consists of an outlet stage (AFC stage) and a driving stage (control stage). This concept combines the advantages of fluidic amplifiers (high (energy) efficiency, compactness) with the advantages of a fluidic oscillator (autonomous generation of a pulsed airflow without moving parts). Therefore it was possible to design a compact actuator system that generates a massive pulsed airflow without moving parts, as a single self-oscillating actuator is able to drive a number of AFC stage actuator elements.
To benefit from this concept it is necessary to drive a series of single element actuator with one oscillator. Therefore the single elements need to be integrated into an actuator array which can be equipped with a single driving stage. Other considerations where easy mountability within the flap, homogeneous distribution of jet velocity and compactness.

It was decided to incorporate a total of five single element actuators within one actuator array. The control port inlets were routed to the mid section of each element to connect those inlets with the outlets of the driving stage.

The length of the actuator array is then 607mm with a height of 105mm. It is mounted at an angle 45° within the flap, so it is sufficiently small to allow for the required skin thickness of the flap.
The CAD drawing of the actuator array is displayed in figure 18.

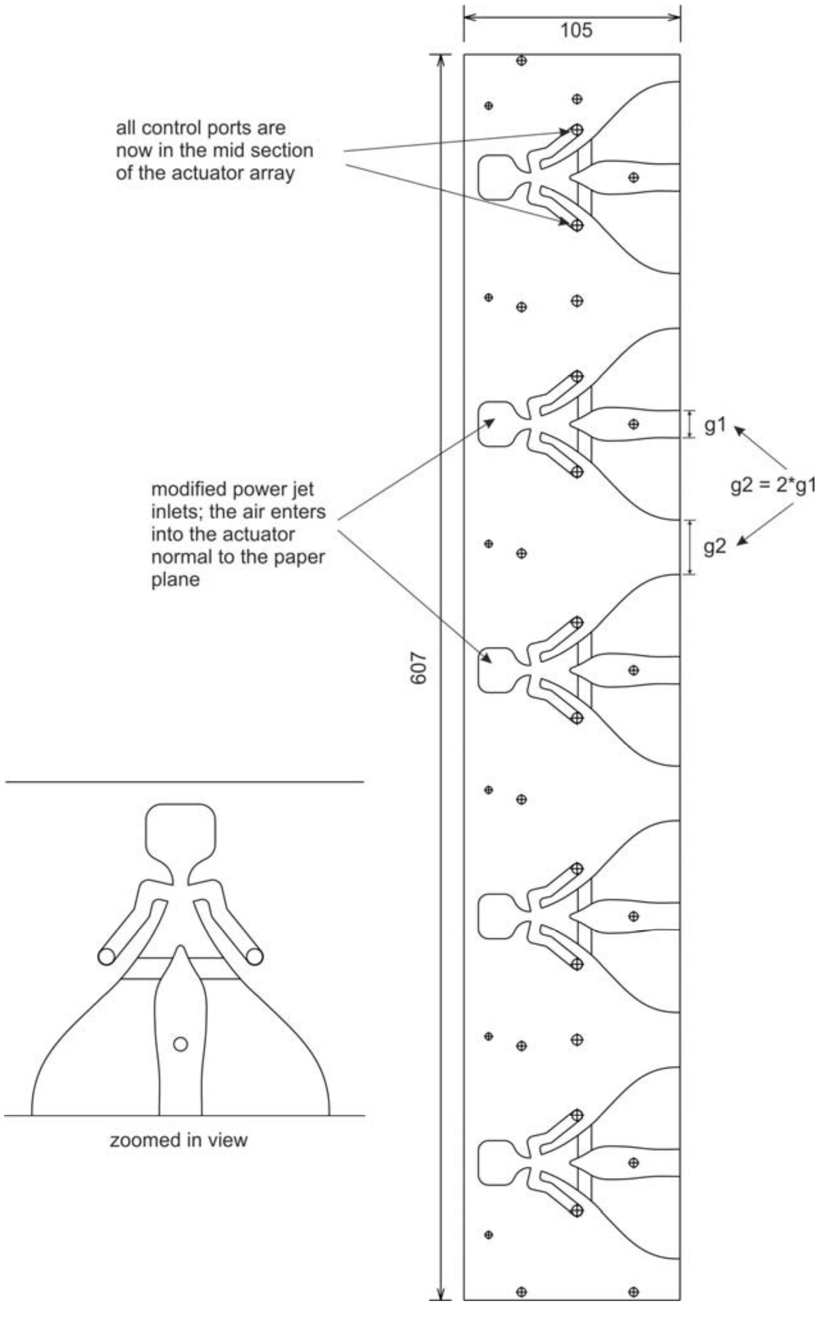


figure 18: CAD drawing of fluidic actuator array

Summary

The single element is based on the output of WP2 and modified in some points to ensure sufficiently short switching times. It was manufactured from aluminium, a plenum was added, and it was equipped with measurement systems. The CAD drawing of the final version of the single element actuator is provided.
In discussions with SFWA projects FloCoSys and AFCIN the number of single element actuators to be integrated into one array was set to 5. The array has then a length of 607mm (spanwise direction) and a height of 105mm. The air inlets were modified to allow for integration into the overall concept of the actuator system and the control port channels were designed to allow for driving the array with one single source of an alternating pressure signal.

WP4

Abstract

Within work package *4* of the project the experimental testing and performance evaluation was completed.
The single element was tested for a broad range of main mass flow rates, control massflow rates, and frequencies. The actuator element showed good modulation at the design point.
The flueric actuator array - consisting of a driving stage and an array of five single outlet stage actuator elements - was subsequently tested for different inlet pressure levels. At the design point of 500mbar above ambient pressure the flueric actuator performed as predicted in numerical studies (WP2) and produced a fully modulated signal at a total flow rate of 100g/sec.

It was therefore possible to provide a working flueric actuator system to other work packages and to other SFWA projects such as FloCoSys and AFCIN for further use.

Results

Single Actuator Element Testing

A single actuator element (see **Fehler! Verweisquelle konnte nicht gefunden werden.**) was tested and its performance was evaluated. For the testing, the actuator element was equipped with Kulite pressure sensors at the control ports, the outlets, and the plenum. In addition the mass flow rates of the power jet and through the control ports were measured. The control signal for the actuator was generated using two FESTO solenoid valves of type MHP2-MS1H-3/2G-M5. This valve allows for volume flow rates of up to 100NL/min (FESTO specification) and frequencies of up to 330Hz. The actuator equipped with sensors is shown in figure 19.

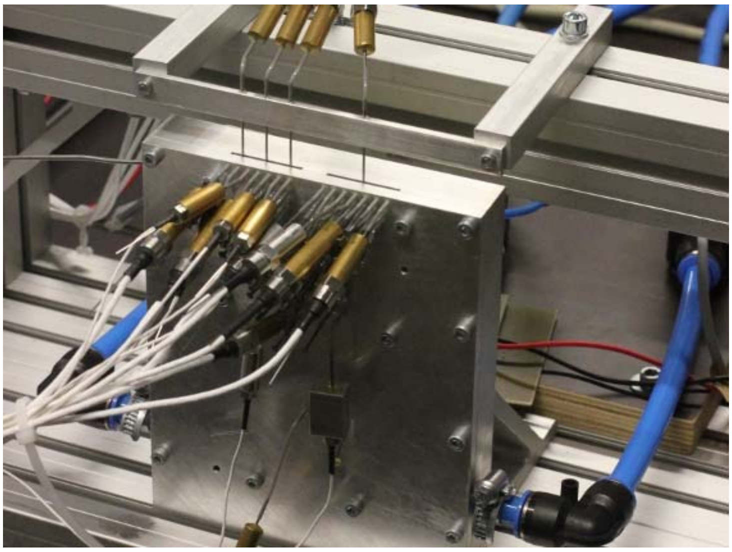


figure 19: actuator elements equipped with pressure sensors

The actuator's design point is at an inlet pressure of 500mbar and a driving frequency of 150Hz. The resulting mass flow rates are 460NL/min trough the power nozzle and 46NL/min through the control ports. However, the behaviour of the actuator was evaluated over a wider range of mass flow rates to investigate off design performance.

The most relevant parameter to characterize actuator performance is the modulation. It is defined as $Mod = \frac{p_{0,\max} - p_{0,\min}}{p_{0,\max}}$, where $p_{0,max/min}$ are the maximum/minimum value of total pressure measured at the actuator's outlets. A modulation of unity implies that the actuator outlet velocity returns to zero during its off-cycle and is therefore desirable. Here, a modulation below 95% is defined to be insufficient performance.

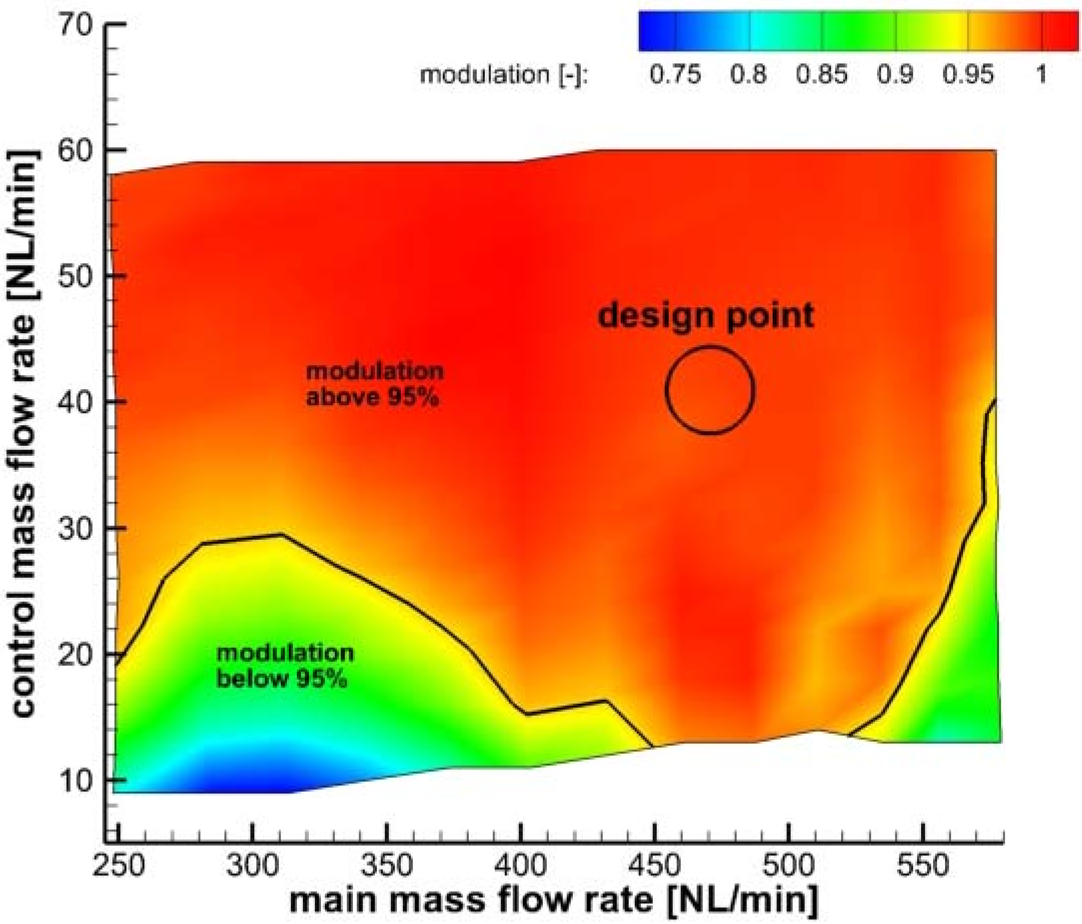


figure 20: modulation for 150Hz actuator operation

The modulation for an actuator operation at 150Hz is shown in **figure 20**. At this frequency the actuator is fully modulated at the design point. There is also sufficient margin to low performance especially with respect to undersupply of control mass flow.

For comparison, the modulation map is shown for two additional frequencies: 112.5Hz in **figure 21** and 187.5Hz in **figure 22**. As expected, the modulation is high for a larger range of main and control mass flow combinations for lower frequencies. When the frequency is increased to a value higher than the design point, the fully modulated range decreases. However, up to a frequency of 225Hz the actuator element operates fully modulated for an inlet pressure of 500mbar and a control flow rate of 10% with respect to the main mass flow rate.

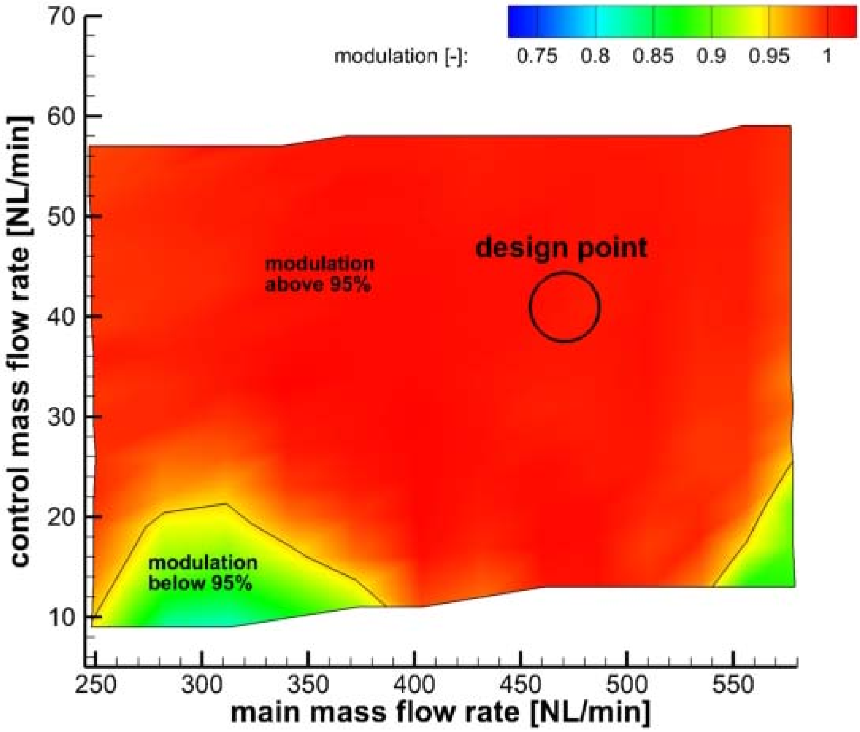


figure 21: modulation for 112.5Hz actuator operation

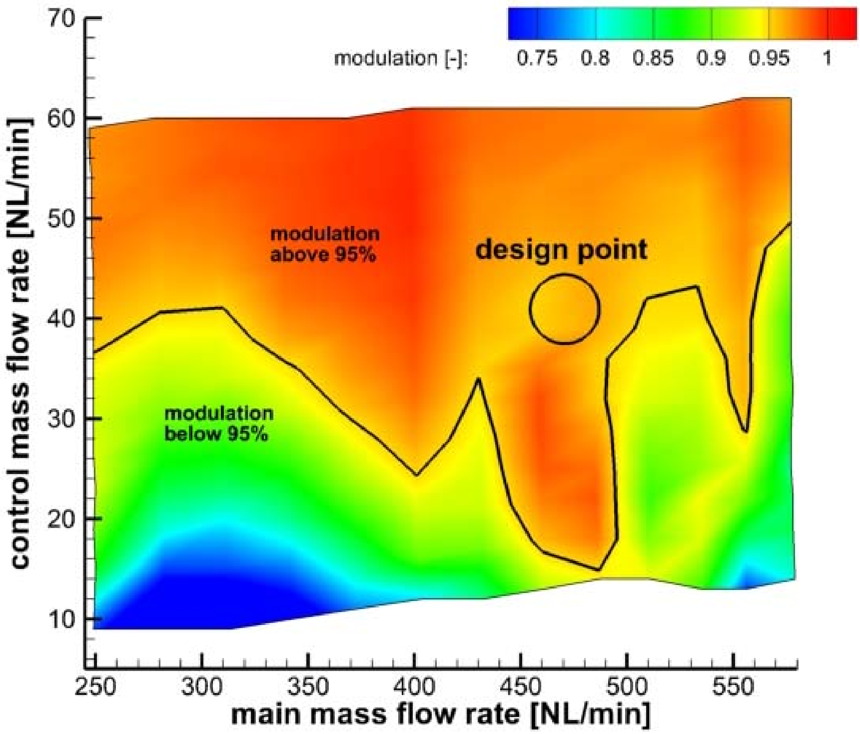


figure 22: modulation for 187.5Hz actuator operation

For the design frequency of 150Hz the resulting minimum and maximum outlet total pressure values with respect to ambient pressure are presented in **figure 23** and **figure 24**. With increasing mass flow rates the maximum total pressure increases. Within the fully modulated range the minimum pressure returns to zero during the off cycle of the actuator. For high control flow rates the total pressure is below ambient pressure, which suggests that then there is *inflow* into the inactive actuator outlet.

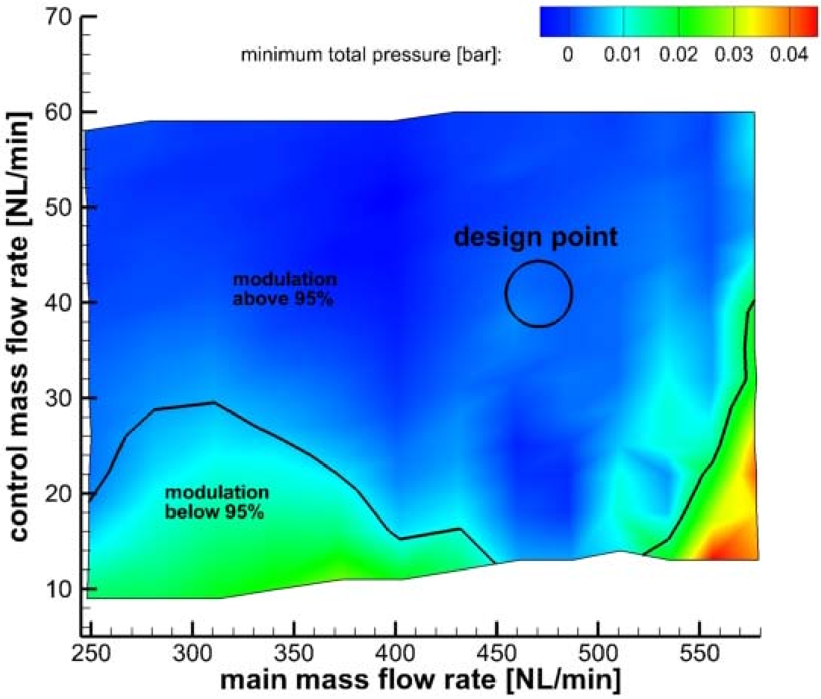


figure 23: minimum total pressure during off-cycle

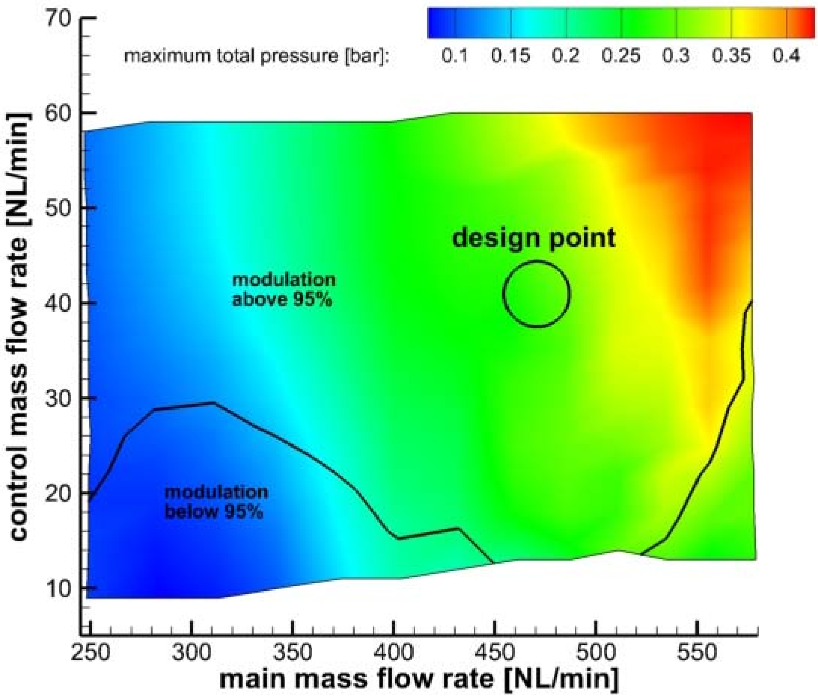


figure 24: maximum total pressure during on-cycle

The switching time (for switching from one outlet to the other at 150Hz) is shown in **figure 25**. For the entire range of tested mass flow rate combination this is below 2ms.

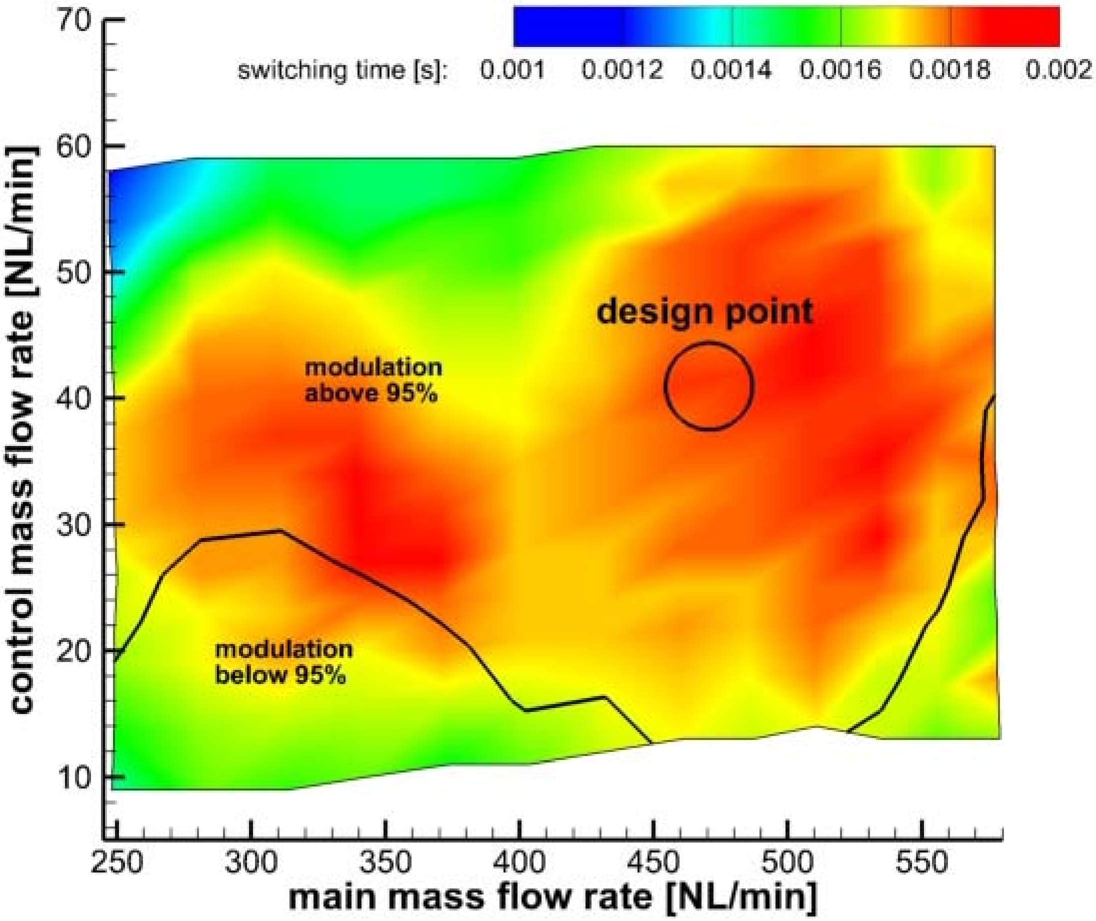


figure 25: switching time of the actuator

For the two frequencies 75Hz (**figure 26**) and 150Hz (**figure 27**) the total pressure (above ambient pressure) for the left and right outlet is shown as time series plots.

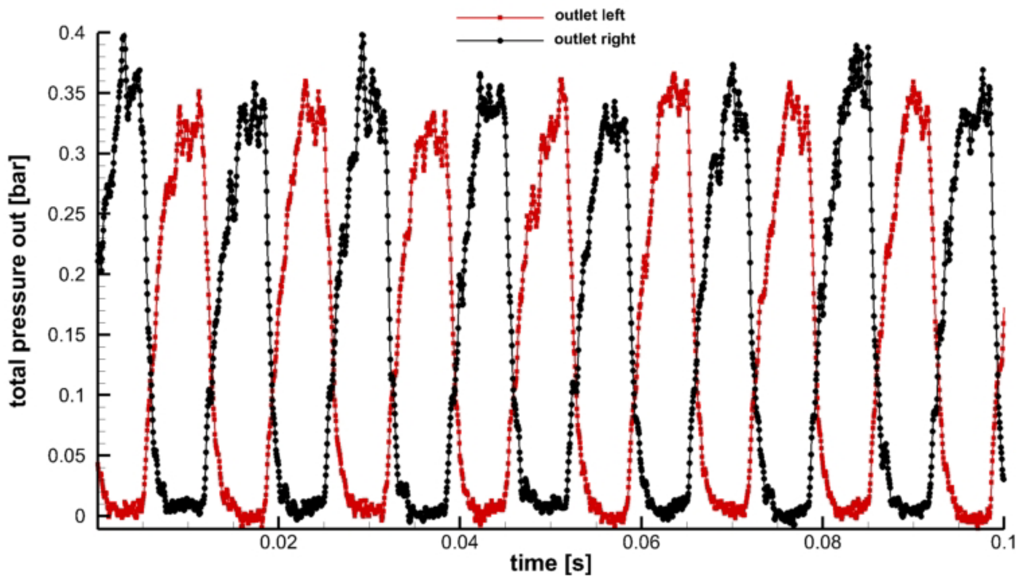


figure 26: time series of total pressure at outlet for 75Hz actuator operation

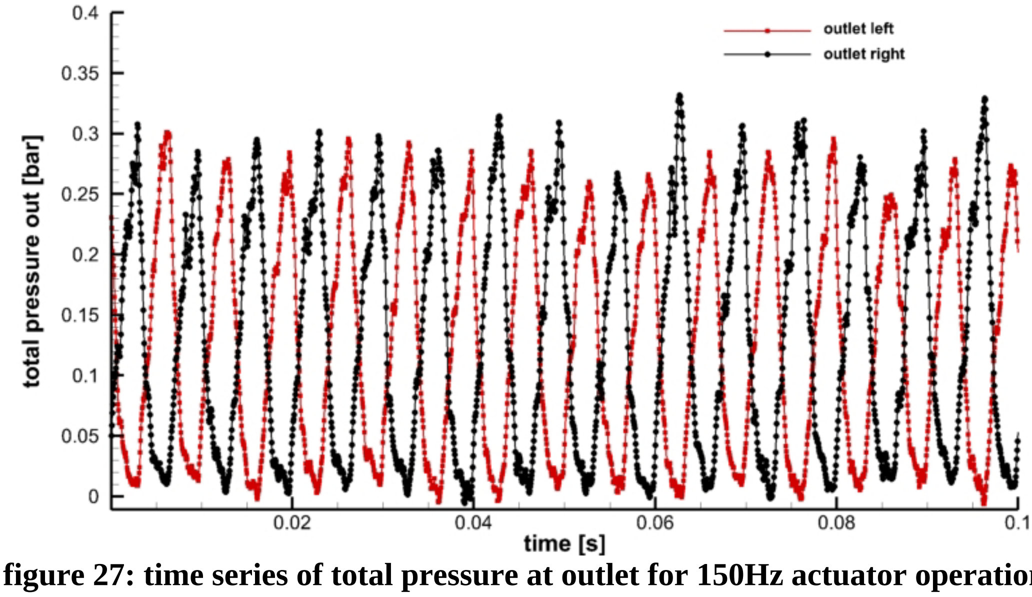


figure 27: time series of total pressure at outlet for 150Hz actuator operation

With the data presented it was therefore shown that the single actuator element operates as expected and was therefore ready for integration into a flueric actuator array.

Flueric Actuator Array Testing

After testing the single actuator element, the flueric actuator array was equipped with sensors and its performance was evaluated. The flueric actuator consists of a plenum, a driving stage, and an outlet stage. Only driving stage and outlet stage are considered to be the core actuator element. Both stages are supplied with the same pressure level through the plenum. Again, the design point for the flueric actuator array is at an inlet pressure level of 500mbar.

As here the frequency is a function of the pressure in the plenum - and therefore the mass flow rate - its dependency is shown in **figure 28**.

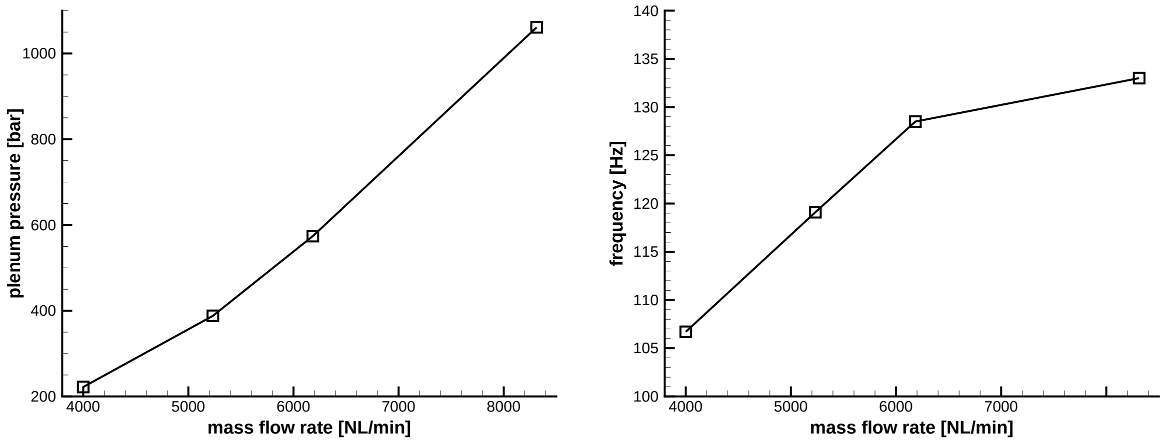
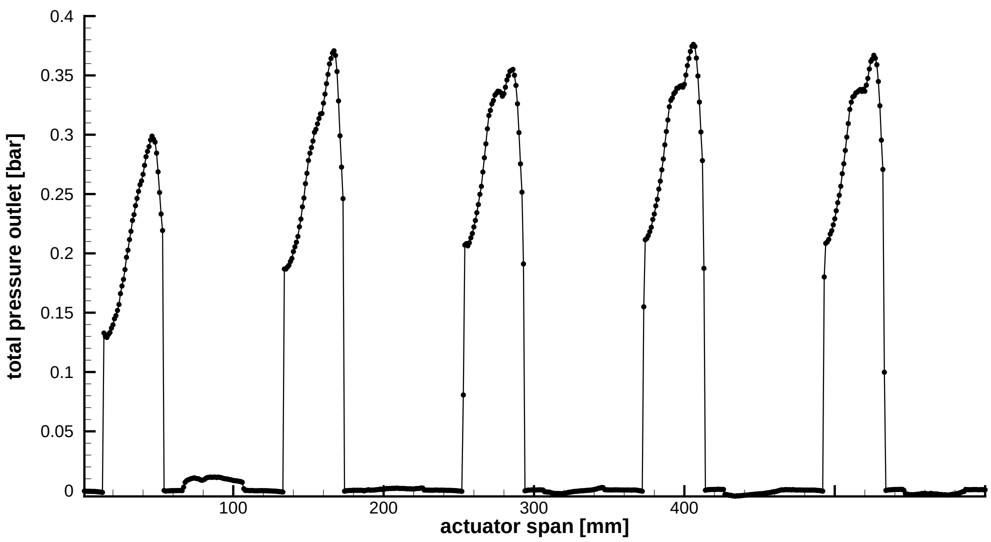


figure 28: correlation of plenum pressure and mass flow rate (left) and frequency and mass flow rate (right)

For the flueric actuator array the total pressure of the air jets was measured at the outlets and is plotted exemplarily in the figure below. The data shown is phase averaged. The pressure is measured relative to ambient pressure. The velocity distribution along the actuators' span of 600mm is sufficiently even and the actuators output is fully modulated for all tested pressure levels applied at the plenum.



Summary

A single fluidic actuator element and a flueric actuator array were investigated in bench top experiments. Pressure measurements were conducted to evaluate the actuators' performance. To quantify the actuators' quality the definition of jet modulation $Mod = \frac{p_{0,\max} - p_{0,\min}}{p_{0,\max}}$ was employed. Independent parameters were plenum pressure, mass flow rate through control ports and power nozzle, and frequency for the single element and plenum pressure for the flueric array.

It was found that the single element actuator performs well in and near the design point.

For the flueric actuator array, the velocity distribution along the actuators' outlets is sufficiently even and the actuators' output is fully modulated for all tested pressure levels applied to the plenum.
It was therefore possible to provide a working flueric actuator system to other work packages and to other SFWA projects such as FloCoSys and AFCIN for further use.

WP 5

Abstract

The work packages 1 through 4 dealt with developing and testing an aircraft scale actuator. Here, the actuator design is downscaled and modified to fit into the space available e.g. in a small- to mid-scale wind tunnel model.
Bench-top tests similar to the ones performed in WP4 document the performance characteristics of this significantly smaller actuator design and proof the fulfillment of requirements specified for the downscaled design.

Results

Single actuator element downscaling

The original actuator was designed to fit into a 70% chord FNG aircraft (a/c) flap. For this geometry, the available height (from lower to upper side) was 80mm and therefore allowed for an integration of the actuator chamber into the core switching body, which is beneficial in terms of reduced total pressure losses.
To adhere to the geometric restrictions of the much smaller wind tunnel (w/t) model, the concept of attaching the actuator outlet to the core switching section was revised.

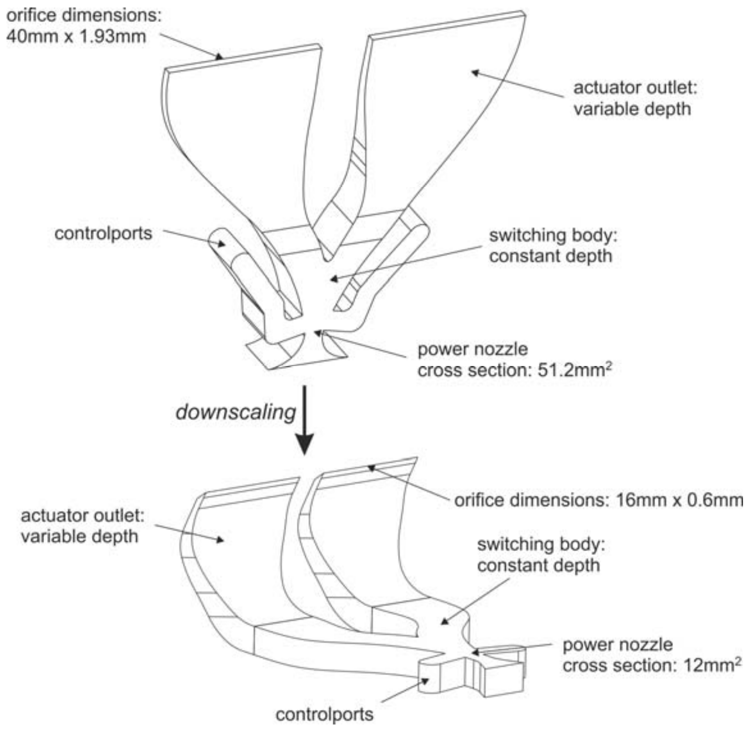


figure 29: Comparison of aircraft scale (top) and wind tunnel scale (bottom) actuator element. The sketches are not to scale.

A comparison of the two actuator designs for large- and small/mid-scale is shown in **figure 29**. For the downscaled actuator the actuator outlet is bent so that the flow is turned by an angle of approximately 135 degrees. The power nozzle cross section (which is a measure of the maximum possible mass flow rate through the actuator) of the w/t scale actuator is approximately 25% of the one of the a/c scale actuator.

Driving stage downscaling and mounting

The driving stage of the a/c scale actuator was scaled to fit the now smaller outlet stage actuator array. Its relative feedback lines length was increased to allow for actuation frequencies in the range between 170Hz and 240Hz. Shorter feedback lines would result in much higher frequencies.

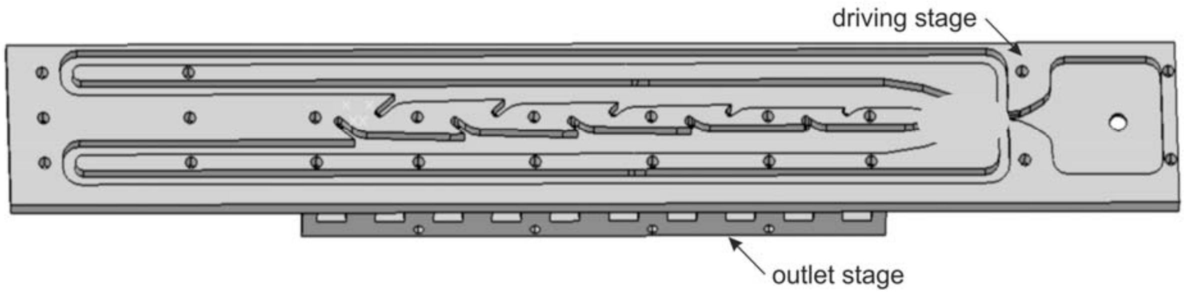


figure 30: downscaled driving stage on top of w/t scale outlet stage array; the actual outlet channels are realized in a different element and not shown here

Mounted driving and outlet stage are shown in
figure **30**. As the driving stage is now significantly longer than the outlet stage, it has to be mounted alternating on the top and bottom side of the outlet array.

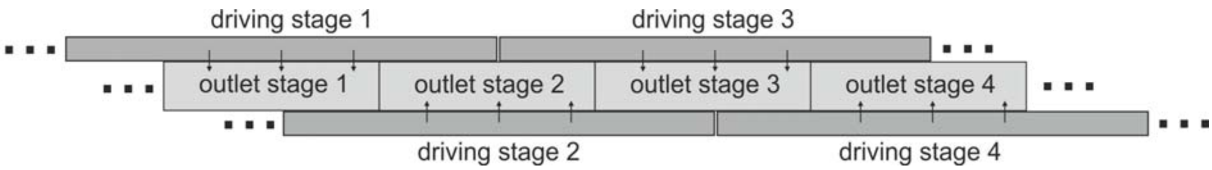


figure 31: principle sketch of staggering driving and outlet stage

This principle is illustrated in
figure **31**. This staggering allows to produce equidistant outlet slots of any desired span. For testing, an actuator was produced consisting of a five element outlet stage and one single driving stage. Both stages were equipped to have individual pressure supplies to study the effect of different mass flow rates through each stage.

Downscaled flueric actuator performance testing

For performance testing the flow rates through each actuator stage were measured. In addition, the total pressure above ambient of the air jets was recorded. This allowed for - similar to the a/c scale actuator - the calculation of modulation as the most relevant parameter to qualify the actuators' performance.

First, the modulation as a function of main and control flow rate is shown in **figure 32**.

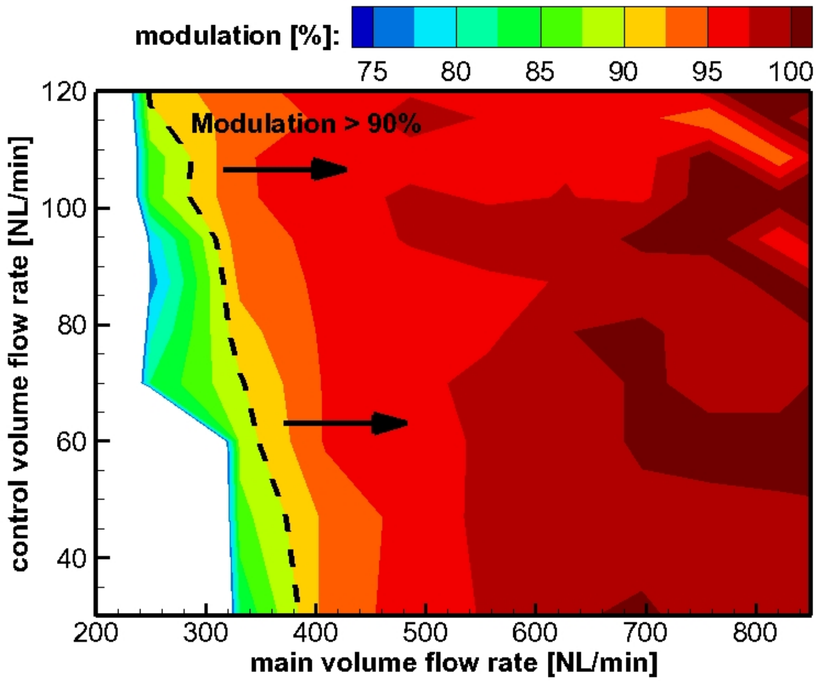


figure 32: modulation depending on main and control flow rates

Starting from a main (outlet) volume flow rate of 400NL/min for a 200mm segment the flueric actuator operates fully modulated (Mod > 90%) for all tested control flow rates. For low main volume flow rates (<550NL/min) increasing the control flow rate results in an increased modulation. Above that value adding control mass does not result in an improved performance.

Another interesting aspect of this downscaled flueric actuator design is the dependency of actuation frequency on control and main volume flow rate. This is shown in **figure 33**.

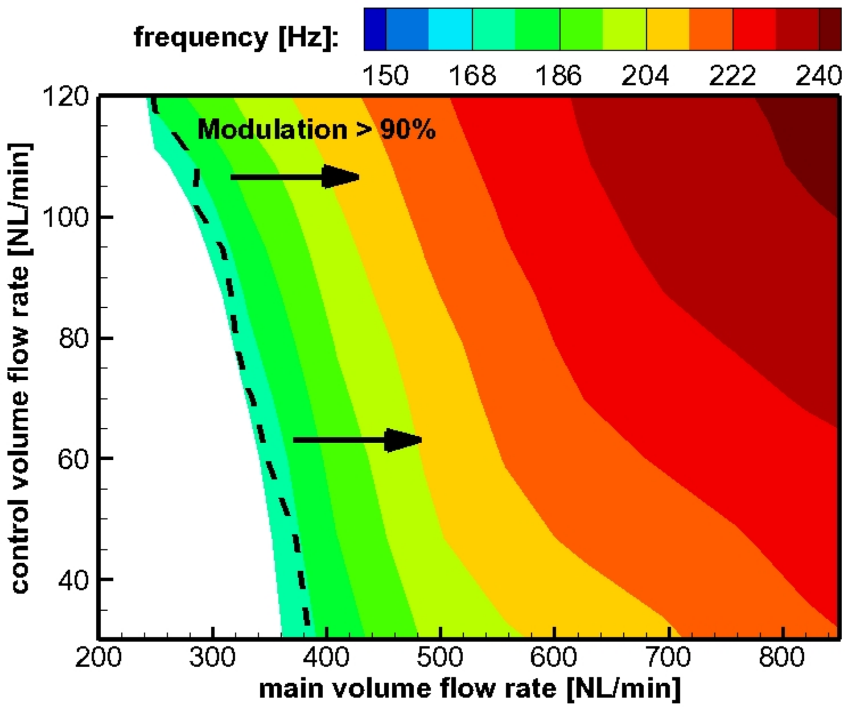


figure 33: frequency depending on main and control flow rates

The actuator's frequency depends mainly on the flow rate through the outlet stage. By increasing the main flow rate from 400NL/min to 800NL/min, the frequency is increased from 170Hz to 220Hz independent of the control mass flow. The control mass flow has a minor influence on the actuators' frequency. By increasing it from 30NL/min to 120NL/min the frequency is increased by approximately 20Hz. For two exemplary parameter combinations time series plots of the total pressure signal are given in **figure 34** and **figure 35**.

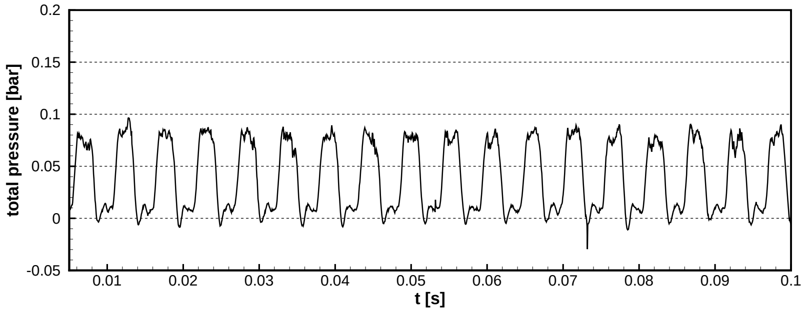


figure 34: total pressure time series for 412NL/min main flow rate and 51NL/min control flow rate

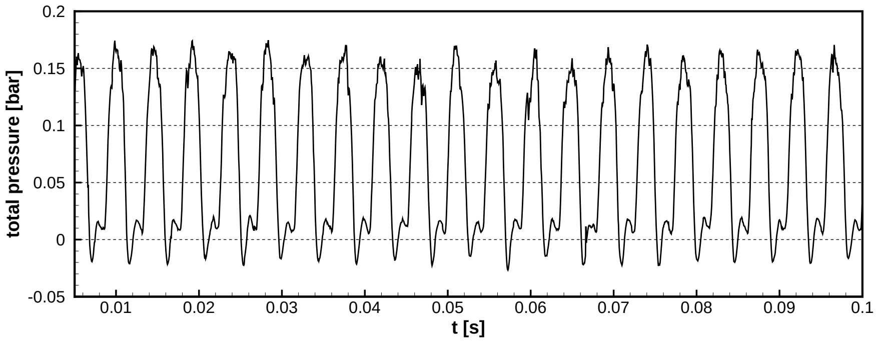


figure 35: total pressure time series for 682NL/min main flow rate and 63NL/min control flow rate

At both points of operation the signal is fully modulated. The data shown reflects the difference in frequency and amplitude for the different parameter sets.

Summary

Starting from an aircraft scale actuator downscaling led to a wind tunnel scale actuator that bases on the same flueric principles. The shape of the outlet structure was modified to fit the actuator into the reduced installation space. Mounting the control stage on top and bottom sides of the outlet stage ensures that this actuator system can be adapted to models of different span.

Extensive pressure measurements proved the functionality of the downscaled actuator. As for the large scale actuator, modulation was considered to be the parameter to qualify the actuators' operability. For main flow rates greater than approximately 2000NL/min/meter, the actuator shows a modulation of more than 90% for all tested parameter combinations. The achievable frequency range lies between 170Hz and 240Hz.

WP6

Technology evaluation

Different flow control actuator concepts have been focus of research in the past decades. The variety ranges from piezo driven Zero-Net-Mass-Flux (ZNMF) actuators, plasma based actuators, and mechanical valves to pyrotechnic actuator and moving pistons. The control authority and frequency range of those actuators vary greatly, all have their pros and cons, and all concepts were tested more or less extensively in lab scale experiments. Only very few concepts were actually tested in flight experiments and no concept was considered for commercial (civil) application.

Besides the problems that any new technology encounters when they are first attempted to be established in a product, the flow control actuator technologies described above lack of robustness, which is a major issue in a safety-first driven environment such as civil aviation. Therefore the trend in past some years is to employ fluidic technology, which was first researched in the 1960s in a completely different context. The beauty is its lack of moving parts (favours robustness) and the efficient conversion of potential energy to kinetic energy. However, so far only single stage oscillator fluidic actuator systems were considered. The novel two stage approach developed within the frame of DT-FA-AFC offers several advantages over those designs:

- High efficiency in terms of total pressure to dynamic pressure conversion, as several diverters are driven by only one much more lossy oscillator.
- Independent (within limits) setting of actuation amplitude and actuation frequency when using two different pressure supplies for diverter and driving stage.
- Reduction of required installation space: Diverters are more compact than oscillators if low frequencies are to be realized, as the operating frequency of an oscillator mainly depends on the length and volume of its feedback lines.

Tests of the overall flow control system have shown that the actuator can operate over a prolonged time without degradation and that it is possible to provide the required energy in a fail-safe manner on a civil aircraft.

It is therefore believed that within DT-FA-AFC a flow control technology was moved one step forward towards flight testing and potential application in a commercial context.

Impact

Concerning the potential impact of DT-FA-AFC it is to note that active separation control by means of pulsed blowing from the flap shoulder is a most promising aspect of the active wing concept and might be a major step towards reaching the ACARE 2020 goals.

Specific impact of flow control may be:

- Reduction of mechanical complexity
- Reduction of needed space for TE flap inside the main element
- Reduction of DOC
- Reduction of weight
- Reduction of fuel consumption

Within this project a (core) fluidic actuator system was developed. The design has high relevance for industry application, as the requirements for the flow control system were specified by SFWA partner Airbus. DT-FA-AFC therefore contributed to furthering the understanding on a rather under researched aspect of flow control - the system aspect (Most research focuses on the understanding of the aerodynamic effect of flow control and the identification of an optimal parameter set.). This impact on the development of flow control hardware was further increased through the close cooperation of TUB with SFWA partner EADS-IW, whose industry perspective on the overall flow control system allowed a detailed study of not only actuator performance, but also of the viability of integrating such a system in the infrastructure of a civil airliner.

The immediate contribution of DT-FA-AFC on flow control hardware design was the establishment of a novel two-stage fluidic actuator concept. The advantages of such a system are (among others):

- High efficiency in terms of total pressure to dynamic pressure conversion, as several diverters are driven by only one much more lossy oscillator.
- Independent (within limits) setting of actuation amplitude and actuation frequency when using two different pressure supplies for diverter and driving stage.
- Reduction of required installation space: Diverters are more compact than oscillators if low frequencies are to be realized, as the operating frequency of an oscillator mainly depends on the length and volume of its feedback lines.

The dissemination of the projects results comprises mostly the provision of input for other SFWA CfP projects, for which the detailed actuator designs were necessary boundary conditions to further their respective goals. Those projects were:

- FloCoSys
- AFCIN
- robustAFC

The final outcome is a highly reliable and durable actuator system, which provides the required flow control authority, is in line with integration requirements and functions without incorporating any moving or electrical components.

Address of project public website and relevant contact details

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