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NLR-TP-2017-424 | November 2017

Design of a Synthetic Jet Actuator for Separation Control

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AUTHOR(S):

S.M. Bardet	NLR
T.A. ter Meer	NLR
A. Gratias	Fraunhofer Institute for Electronic Nano Systems ENAS
M. Lipowski	Fraunhofer Institute for Electronic Nano Systems ENAS
M. Schüller	Fraunhofer Institute for Electronic Nano Systems ENAS
P. Weigel	Fraunhofer Institute for Electronic Nano Systems ENAS

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Perez Weigel
Fraunhofer Institute for Electronic Nano Systems ENAS
Research Associate
Technologie-Campus 3, 09123 Chemnitz, GERMANY
perez.weigel@enas.fraunhofer.de

Martin Schüller
Fraunhofer Institute for Electronic Nano Systems ENAS
Research Associate

André Gratias
Fraunhofer Institute for Electronic Nano Systems ENAS
Research Associate

Mathias Lipowski
Fraunhofer Institute for Electronic Nano Systems ENAS
Research Associate

Theo ter Meer
NLR – Netherlands Aerospace Centre
R&D Engineer
Anthony Fokkerweg 2, 1059 CM Amsterdam, NETHERLANDS

Michiel Bardet
NLR – Netherlands Aerospace Centre
Senior Application Engineer

ABSTRACT

This paper describes the development of a piezo-electric Synthetic Jet Actuator (SJA) in the AFLoNext project. AFLoNext (Active Flow – Loads & Noise control on Next generation wing) is a project within European Union's 7th Framework Program. One of the main goals is the application of Active Flow Control (AFC) techniques, such as SJAs and Pulsed Jet Actuators (PJAs) in two different application scenarios to evaluate the potential benefit for retrofit of current aircraft and also for future aircraft designs. For large-scale wind tunnel testing, an actuator panel with 85 SJAs including the drive electronics system was designed and pre-tested in a laboratory environment. The performance exceeds 100 m/s with outlet nozzles of 2.5 mm diameter and a span wise clearance of 10 mm. A second actuator design was prepared for the application on the outer wing region and was investigated in an harsh environmental test campaign. Two rows of five actuators were integrated in a panel with 10 x 0.5 mm² slotted outlet nozzles. With this design also velocities exceeding 100m/s can be measured. The actuators withstand different harsh environmental conditions including extreme temperature, rain, mechanical vibration and shock. With the results of the project, a Technology Readiness Level (TRL) evaluation will conclude the maturity of the technology. Depending on the final test and evaluation results, achievement of TRL4 is expected.

KEYWORDS: *Synthetic Jet Actuator, separation control, robustness test campaign, wind tunnel evaluation*

1 INTRODUCTION

1.1 AFLoNext technology streams

AFLoNext is a project within the European Union's 7th Framework Program. One of the main goals is the application of Active Flow Control (AFC) techniques, such as Synthetic Jet Actuators (SJA) and Pulsed Jet Actuators (PJA) in two different application scenarios to evaluate the potential benefit for retrofit of current aircraft and also for future aircraft designs. An overview of the different Technology Streams (TS) in the project is depicted in Figure 1. In TS2 the application of Synthetic Jet Actuators on outer wing region is evaluated. For the actuator development in TS2 the focus was on the robustness of the system. A detailed test campaign for the assessment of the system in different harsh environmental conditions was performed. A second application scenario is evaluated in TS3. The actuators are applied on the wing/pylon junction to counter the lift losses caused by the closely-coupled integration of Ultra High Bypass Ratio (UHBR) turbofan engines. The other Technology Streams within the project deal with other approaches for reducing emissions for future aircraft, such as hybrid laminar flow control or noise and vibration mitigation.

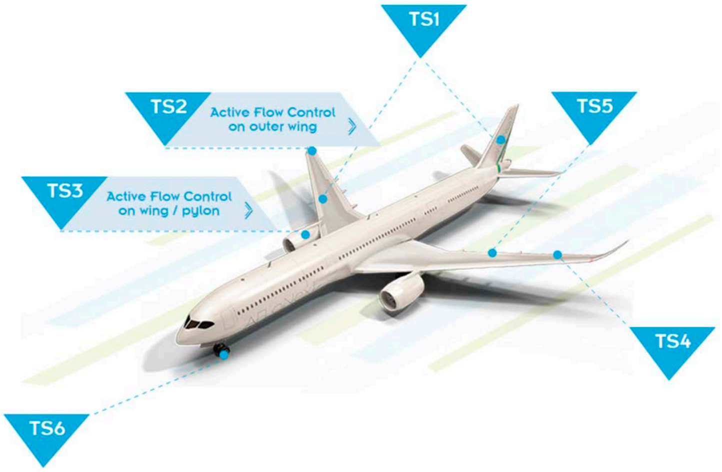

Figure 1: Overview of Technology Streams for the AFLoNext project[1]

1.2 State of the Art review

It has been known for two decades that SJA are able to manipulate an air flow [1][2]. This effect can be used for fluidic active flow control, especially for aerospace applications [3][4]. Apart from this, their potential application field is very wide. SJA can be used for cooling in electronic devices [5], jet vectoring [6], pumping, mixing enhancement and for many other purposes [7][8]. The device consists of a small cavity which is closed on one side by a vibrating transducer element. On the other side of the actuator a nozzle connects the cavity with the external environment. The vibration of the transducer element leads to a periodic suction and exhausting of the surrounding fluid through the nozzle. Due to the pulsed blowing a synthetic jet is formed in front of the nozzle, even if the net mass-flow through the actuator is zero [1]. The advantages of SJAs are that they do not need an external compressed air supply, are relatively small and have a low power consumption. Challenging is their limited performance with respect to possible peak velocities and the interdependence of the resonance behaviour and environmental conditions [9]. The development in AFLoNext aims on a progress towards feasible actuators for future aircraft integration. The identified drawbacks of the actuators are addressed and the designs focus on both aspects - high performance as well as high robustness - to meet the industrial requirements.

The majority of the described actuators in literature use piezo-electric transducers [10], but also actuators with shape-memory alloy based transducers [16] or mechanical piston actuators [17][18]

[1] Source: http://www.aflonext.eu/technology-hybrid-laminar-flow-active-flow-control-noise-reduction-vibrations-mitigation-8

are used to drive SJA. Next to this kind of transducers, also actuators with electro-dynamic transducers are described [19]. The normal velocity range of the described actuators is typically below 50 m/s. The different geometrical parameters of the actuators make an overall benchmark of different prototypes difficult, because the peak velocity depends on drive frequency, nozzle geometry, cavity volume and even the used clamping method for the transducer element. A review of the current state of the art has identified four main aspects for further optimization:

- Transducer element optimization calculations and simulations;
- Modelling and optimization calculation for geometrical parameters for the fluidic resonator;
- Clamping and electrical contact for transducer element integration;
- Increased robustness against harsh environmental conditions.

The requirements given by the industrial partners cover constraints of the following aspects:

- ***System installation and assembly room***
- ***Active flow control performance***
- Energy consumption
- ***Materials***
- Operability
- Redundancy
- ***Structural Considerations***
- Weight

Not all requirements apply to the hardware system which is evaluated in wind tunnel tests. The focus has been the bold marked aspects above to keep the effort in line with the available time. All other aspects will be addressed in further developments of the actuator system towards a future flight test.

2 ACTIVE FLOW CONTROL ON THE WING / PYLON JUNCTION

2.1 Concept for Wind Tunnel Evaluation

The main goal of the system design was the compliance with the requirements that apply to the integration in a 1:1-scale wind tunnel model. Because of the limited budget and time, a cost optimized solution is designed with the option to further miniaturize and integrate the system in future design iterations. The final specification of the actuators was not available during the design phase of the system, so certain assumptions had to be made. This led to the modular approach of the system. Changes on the system can be made more easily than with fully integrated systems.

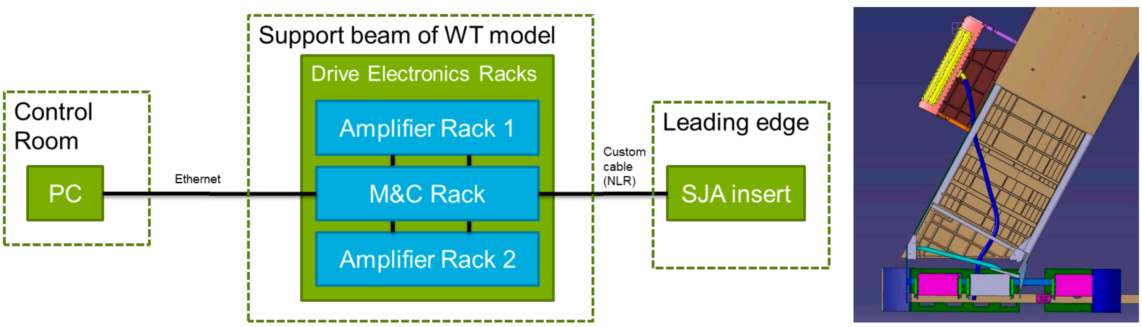

Figure 2: System design concept for the SJA System (left), top view of wind tunnel model CAD model with SJA insert (yellow), custom actuator connection cable (blue), and drive electronics subracks (magenta & grey)

An overview of the complete system design for the SJA AFC system is shown in Figure 2. It consists of three main parts:

- The SJA Insert for the housing of the actuators and the integration in the wind tunnel model;

- Signal conditioning, actuator excitation and monitoring equipment, located as close as possible near the wind tunnel model (Drive Electronics subracks);
- The HMI (Human Machine Interface) computer for control, data recording and visualisation.

The Drive Electronics system consists of two High Voltage (HV) Amplifier subracks that are controlled by a Measurement & Control (M&C) subrack. It provides high-voltage excitation signals for the actuators and monitors the current status of the system and the individual actuators.

2.2 Wind tunnel test actuator design

The Synthetic Jet Actuators developed in AFLoNext are based on piezo-electric transducers. They are equipped with a two-pin electrical connector for the HV input signal and have a 45° inclined circular outlet with a diameter of 2.5 mm on the upper side of the housing. The outlet has a sealing for an air tight connection with a common top cover plate. The actuators have a polymeric housing.

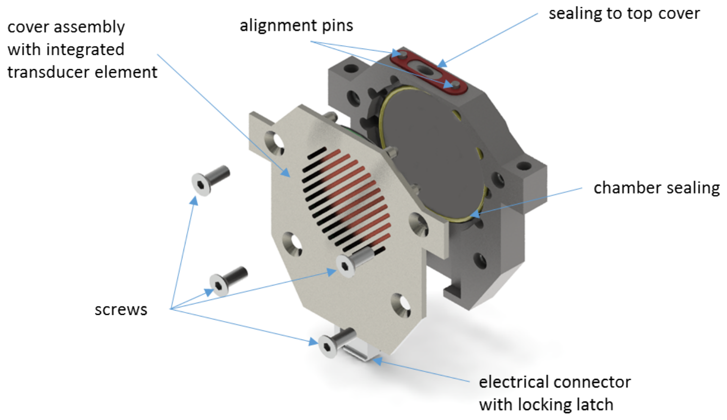

Figure 3: Synthetic Jet Actuator

The electrical parameters of the piezo-electric transducer determine the design of the drive electronics system. The following parameters were used to calculate the required amplifier power:

- Capacitance of transducer element: up to 200 nF
- Drive frequency in mechanical resonance: up to 2.0 kHz
- Maximum excitation voltage: 200 V_{pp} (unipolar)

The typical performance of three actuators is shown in Figure 4. Velocities up to 100 m/s are possible with a peak to peak current consumption of 0.15 A to 0.2 A. At the resonance frequency the power consumption of an actuator can be calculated using the average current $\boldsymbol{I_{av}} = \frac{1}{\pi} \cdot \boldsymbol{I_{pk}}$. With 200 V excitation voltage the power consumption of one actuator is 9.6 to 12.7 W.

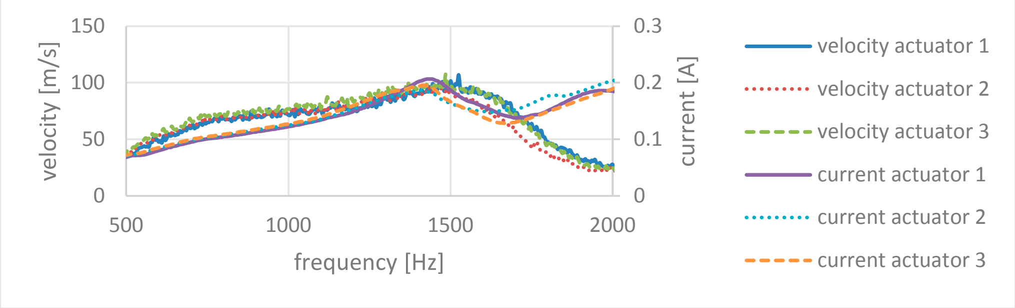

Figure 4: Actuator velocity and current versus frequency

2.3 Drive electronics design

Amplifier subrack

The initial aim of the market survey was to focus on the use of Commercial Off-The-Shelf (COTS) equipment as a complete solution to drive all required actuators. The leading specifications were the ability to drive large capacitive loads (100 SJAs of 200 nF each) in combination with sinewave excitation voltages of at least 150 V_{pp} and a frequency of 3 kHz. Because of the required high full power bandwidth with the associated high slew rate, this leads to HV amplifiers that must be able to deliver a current of about 28 A_p in total. COTS products with such specifications (total power exceeding 2 kVA) were not found on the market. Only high voltage power amplifiers that are specifically designed for driving reactive loads are suitable for this application, as regular amplifiers would suffer from stability issues and have difficulty to cope with the high dissipation in the power stage. Also, flexible grouping of actuators is desired with the option to drive various groups with different signals. The high total power demand and the grouping requirement called for a more flexible custom solution based on smaller COTS HV driver amplifiers.
Various desktop and modular amplifiers were evaluated from such manufacturers as Trek, Physik Instrumente, Sonitron, Tegam, Piezo Systems, and PiezoDrive. The most appropriate amplifiers with regard to technical performance, compactness, and price are manufactured by PiezoDrive. The selected amplifier module is a fan-cooled OEM module from PiezoDrive, type MX200 [20]. This module can be configured for a maximum amplitude of 100, 150, or 200 V_{pp}. Maximum output current depends on the selected voltage mode. For the 200 V setting, the maximum output current is 220 mA_{RMS} and 1 A_p. This corresponds to driving 250 nF at 2 kHz at 200 V_{pp}. The output is current limited and tolerates overloading and short circuiting, making it a robust solution.

Figure 5: Amplifier subrack - front view

An amplifier subrack (Figure 5) is designed and manufactured that contains twelve MX200 amplifier modules and the DC power supplies for the amplifiers. Three amplifier modules are combined on one carrier board; four carrier boards and two COTS power supply modules [21] are incorporated in one amplifier rack. The subrack is a 19" unit with perforated top and bottom panels. They allow ventilation while at the same time shielding the dangerous voltages that exist on the amplifier modules. A fan tray is fixed to the bottom of the rack, in order to remove the heat that is dissipated in the amplifier modules.

Measurement & Control subrack

Monitoring of the actuators is necessary to have a feedback on the actual behaviour during the tests. Different approaches for the monitoring can theoretically be used, but have to be feasible in terms of integration, costs and handling. A characterization of the performance with conventional air speed measurements with hot-wire anemometry is not possible during the tests. Due to the dynamic alternation of the suction and blowing phase in one cycle, a very fast system is needed. Pitot tube systems have the drawback of low-pass filtering the velocity signal due to fluidic capacitance in the tube and therefore can only be used at low frequencies. Also, the integration in the small nozzle structures would be very challenging. A second solution is to monitor the pressure in the cavity of the actuators and the outer pressure to calculate the velocity through the nozzle based on the pressure difference with common analytical equations. Small pressure sensors which can measure the cavity pressure fast and accurately are however too expensive for integration in each actuator. Therefore only the possibility of measuring the electrical characteristics of actuator voltage and current consumption is available to provide feedback of the actuator behaviour. The dynamic behaviour of the actuator can be observed by measuring the frequency-dependent current consumption and the phase angle between voltage and current signal.

Figure 6 shows the connection between the Amplifier subracks, the Measurement & Control (M&C) subrack and the actuators. The HV signal of the amplifiers is routed through the M&C subrack. In this subrack a measurement circuit monitors the voltage and current signal. From the M&C subrack the HV signal is connected to the actuators. Up to four actuators can be connected in parallel to a single output of the M&C subrack.

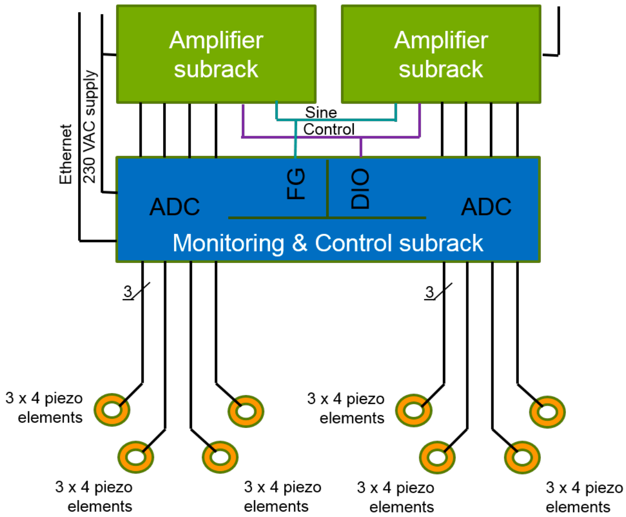

Figure 6: System Design for AFLoNext SJA System (ADC = Analog-Digital Converter, FG = Function Generator, DIO = Digital Input/Output)

The M&C subrack has integrated microcontroller-based data acquisition circuits. The microcontrollers measure the signals' current and voltage. Moreover, they provide an analogue input signal for the HV amplifiers. The subrack is only functional when it is connected to a remote measurement computer. On this computer a software application provides a user interface to control the subrack and setup the drive signals as well as collect the data measured by the microcontrollers.

Cabling

Cable harnesses were manufactured for the signal exchange between the M&C subrack and the two Amplifier subracks, and also for connecting the actuators to the M&C subrack. The latter cables are five meters long. They carry potentially lethal signals and are manufactured using high-voltage wire in twisted pairs. Sets of these twisted pairs are contained in braids that provide a protective shield that ensures safety even in case a cable is damaged mechanically. Inductance of the long cable needs to be kept below a specified value, in order to avoid resonance with the SJA capacitance at a frequency in or close to the signal bandwidth.

Software

The windows software for control of the M&C subrack is implemented in C# programming language. It can be used to set up the drive parameters for every amplifier and measure the voltage and current on every channel out of the total of 24. Furthermore, it monitors the overload status of the amplifiers and gives the possibility to enable or disable individual amplifiers. To identify the resonance behaviour of the actuators and track if there are changes related to the different outer flow conditions, the software is capable of performing a frequency sweep and providing data for peak current versus frequency plots. This data can be used to check if the resonance frequency has changed and drive parameters can be adapted accordingly. For the wind tunnel test a common time synchronization signal will be provided by the wind tunnel system via the UDP protocol. Therefore the software monitors and logs also the UDP ports so that the acquired data of the measurement system can be easily linked to the specific experiments during the test campaign. Figure 7 shows the software user interface with the different sections:

(1) Enable/Disable of amplifier boards with overload signal indicators;
(2) Setup of drive signal amplitude and frequency;
(3) Setup of Measurement file path and sweep parameters;
(4) Setup of Range for plots;
(5) Current and voltage plots for every amplifier with setup block for;
    a. Drive signal and frequency
    b. Enable
    c. Overload indicator
(6) UDP monitoring.

Figure 7: Software interface

2.4 Laboratory testing of the system

The Drive Electronics system was tested with the SJA Insert that is used for the wind tunnel tests. Figure 9 shows the setup for the laboratory tests.
Due to manufacturing tolerances the performance of the actuators is not identical. The panel was characterized by means of a hot wire anemometer. The results are shown in Figure 8 including the scattering of the performance. The drive electronics system was capable of driving all actuators without going into overload state. The capacitance of one actuator is approximately 85 nF. Up to four actuators are connected to one amplifier in parallel, which corresponds to a capacitive load of 340 nF.

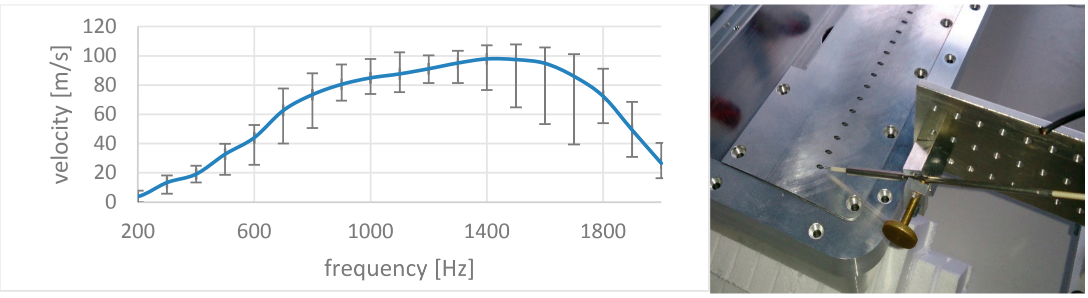

Figure 8: Statistical test results of all 84 actuators (left) / hot-wire velocity measurement setup (right)

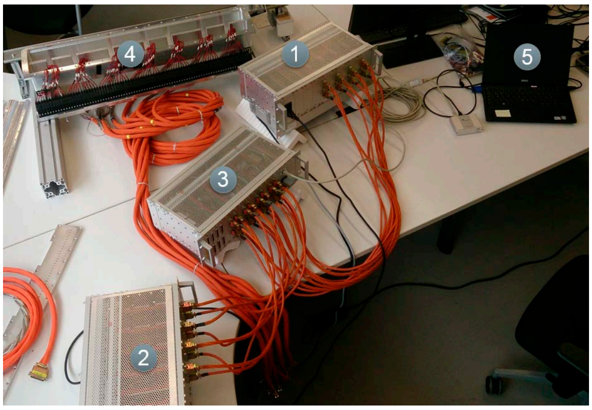

Figure 9: Setup for ground test (1 and 2 – Amplifier subracks, 3 – M&C subrack , 4 – SJA Insert with actuators , 5 – Remote Control Computer)

3 ACTIVE FLOW CONTROL ON THE OUTER WING

3.1 Concept for Robustness Test Campaign

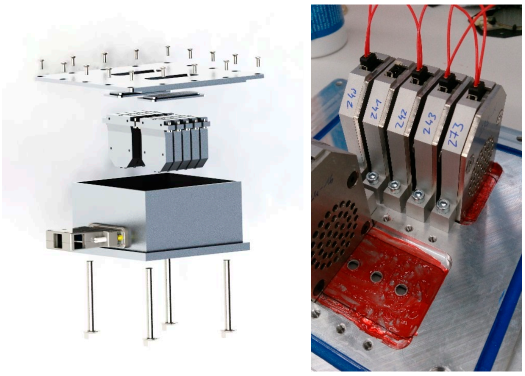

Figure 10: Exploded view of actuator panel for a harsh environmental test campaign (left) and actuators mounted in top cover plate (right)

For the second application scenario considered in AFLoNext, a panel with ten actuators in two rows was designed and manufactured. This panel was designed for a harsh environmental test campaign conducted by INCAS in Bucharest. The panel integrates two different nozzle geometries. One row has 10*0.5mm² with 30° nozzle inclination. The second row basically has the same geometry, but with a 45° inclination with respect to the surface. All actuators within the panel are connected to one common 25-pin D-Sub connector. Twenty pins are used for connecting every single actuator with a 2-pin electrical interface. The remaining five pins are used for grounding the panel to protective earth, when the drive electronics system is connected. The system is driven by an amplifier system with attached measurement circuit for current and voltage monitoring. The drive system is an in-house development by Fraunhofer ENAS and has integrated two HV amplifiers with maximum peak output voltage of 150V. Ten measurement channels – five per amplifier output – for voltage and current monitoring are available. The system is connected via USB interface to a control computer and a LabVIEW software is used to set up the drive signal and monitor the actuator signals and their current consumption.

3.2 Robust Actuator design

The actuators are designed with an aluminum housing. The same transducers as for the actuators for wing-pylon integration are used. The interface to the top cover is a circular hole with 4 mm diameter.

The nozzle element adapt the geometry from this 4mm hole to inclined slots of 10*0.5mm² with 30° or 45° inclination. The choice to use aluminum as the housing material was based on the extreme environmental conditions the actuators had to withstand during environmental DO1060 tests.

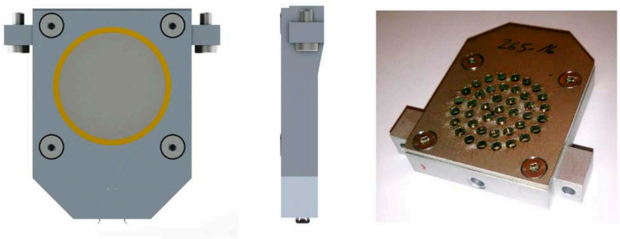

Figure 11: SJA front view (left), side view (middle), prototype actuator (right)

3.3 Results of test campaign

Before starting the tests campaign the performance of every single actuator in the panel was characterized using a hot-wire anemometer. To verify the influence of the harsh environmental tests on the actuator panel the characterization was repeated after every test. The results showed whether the actuators still worked properly or whether the performance has changed. The different tests are an indicator of any critical weak points of the current design and will be detailed to exactly identify the individual failure mechanisms and derive adaptions of the design out of them.

The initial performance of the panel is shown in the graphs below. Due to the different nozzle geometries the resonance frequency is different between the two rows. Also the performance is not the same. The detailed cause-effect relationships have to be examined more deeply in further research on this topic.

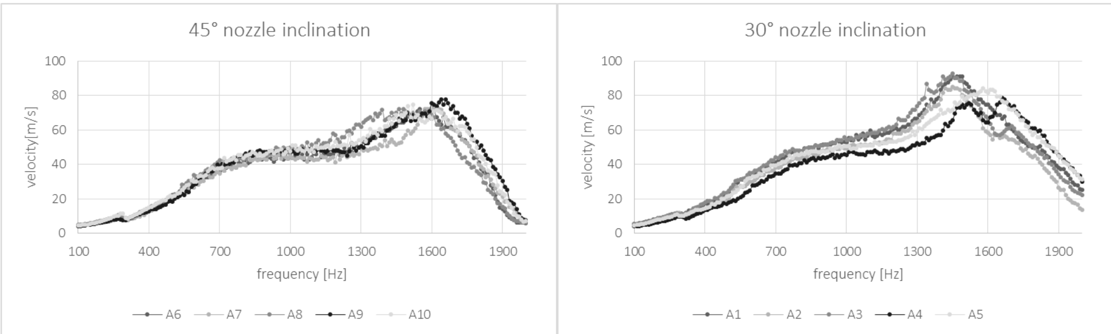

Figure 12: characterization results for the actuator panel before the harsh environmental test campaign

Most of the tests are performed using the EUROCAE ED-14G (RTCA DO-160G) environmental test standard for airborne equipment. More detailed information can be found in [22] where the test campaign is described and some of the results are shown.

4 OUTLOOK

The goal of the test campaign was the technology evaluation and assessment of the Technology Readiness Level (TRL). With the current results of the environmental test campaign the actuator system is classified as TRL 3. With positive results out of the wind tunnel test TRL 4 may be achieved. The further development on the actuators will focus on aircraft integration and addresses the identified drawbacks of the current design to find more robust solutions. The results of the project AFLoNext will be transferred to future projects to mature the technology towards higher technology readiness levels. This will include a miniaturization of peripheral electronic systems and a further optimization of the actuator performance with integration of additional internal sensors for enhanced monitoring and control.

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NLR

Anthony Fokkerweg 2
1059 CM Amsterdam, The Netherlands
p) +31 88 511 3113 f) +31 88 511 3210
e) info@nlr.nl i) www.nlr.nl