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ONGOING PROGRESS IN FLOW CONTROL ACTUATORS AND REQUIRED DRIVE ELECTRONICS

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ABSTRACT:

In the frame of the Cleansky 2 projects SYNJET3C and FLOCOS, CEDRAT TECHNOLOGIES (CTEC) and TRISITEC are collaborating with both FRAUNHOFER and ONERA institutes, two major European research leaders in the development of **S**ynthetic **J**et **A**ctuators (SJA) for Aerospace applications. While SYNJET3C project is dedicated to SJA mechanical designs and optimisation, as well as testing including wind tunnel tests, FLOCOS project is dedicated to the design and manufacturing of a specific SJA drive Electronic called **SADS** (**S**ynthetic Jet **A**ctuator **D**rive **S**ystem).
SYNJET3C project is a first opportunity of a large collaboration involving both FRANHOFER and ONERA as experts on SJA designs, tests and optimisation, with two SME's TRISITEC and CTEC aiming at providing hardware solutions, and potential recurrent manufacturing capabilities for future projects.
FLOCOS project is focused on FRANHOFER SJA technology, aiming at providing dedicated drive electronic with potential future recurrent manufacturing capabilities insured by TRISITEC and CTEC. ONERA is not involved in FLOCOS project, but the expected outcomes are expected to benefit to all European technologies on SJA domain.
This publication shall present ongoing results for both projects, which are expected to demonstrate the birth of a relevant European manufacturing industrial consortium on SJA.

1. SYNJET3C PROJECT- IMPROVING THE SJA MODELLING KNOWHOW

1.1 Background and objective

In the aim at reducing the energy consumption of the aircrafts, and improve the lift, **A**ctive **F**low **C**ontrol (AFC) is considered as a promising concept. Several H2020 projects deal with this technology. Among the mechanisms developed, two different principle are considered. Actuators named **P**ulsed **J**et **A**ctuators (PJA) are based on a pressurized air volume and a valve which pulses the air outside of the vane. The second kind of actuators called **S**ynthetic **J**et **A**ctuators (SJA) is based on zero net mass flux. This has the advantage of reducing the mass of the device and simplifying its integration in the aircraft. SYNJET3C H2020 project aims at first improving the knowledge of SJA. Starting from an existing SJA (see Figure 1), tests, calculation and simulation are carried out, firstly to evaluate the performance of the actuator and secondly to understand the behavior of the actuator and its sensitive parameters, and finally, to propose the design of a new SJA with better performances.

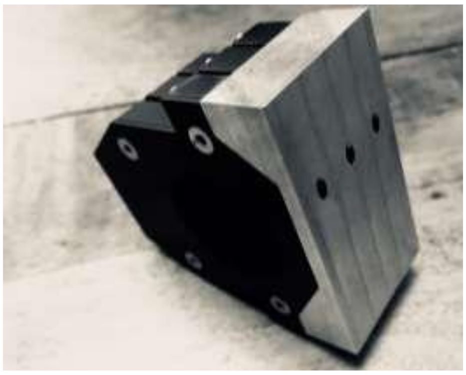

Figure 1: Existing Fraunhofer SJA studied in SYNJET3C

1.2 Experimental testing on existing SJA

The study starts from an existing SJA based on the displacement of a piezoelectric membrane connected to a fluidic cavity. The cavity output is a nozzle allowing the sharing of air with the outside. A test campaign is quiescent air conditions has been performed, varying the dimension of the nozzle and cavity. For each configuration of actuator, the cavity pressure, membrane displacement and output jet velocity have been measured.

The summary of this test campaign is available on Figure 2. It appears that the membrane properties and the geometry of both cavity and nozzle have an influence on the output jet velocity, and of the resonance frequency of the device. The Cavity named K1 associated with the nozzle D01 give the best performance with an output jet velocity about 50m/s.

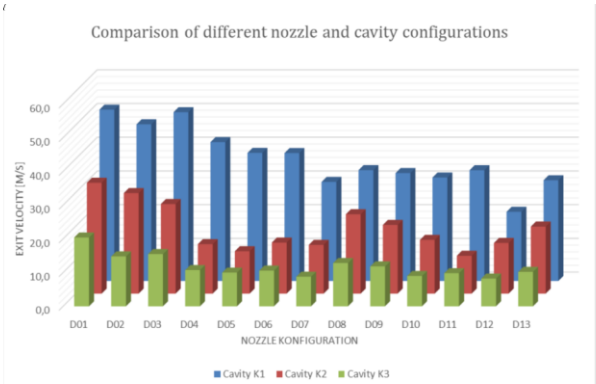

Figure 2: SJA characterization in quiescent air condition

On the other hand, another test campaign has been performed using only one configuration, in cross flow conditions, in a wind tunnel facility. The goal of cross flow conditions testing is to characterize the influence of the SJA on the boundary layer thickness and turbulence ratio.

1.3 Characterization of the fluidic cavity

The fluidic cavity has been modeled using CFD analysis, with a fixed meshing. The membrane displacement has been applied to the cavity model as a forced velocity of the fluid on the membrane surface. The velocity profile is periodic following a sinusoidal temporal evolution. The calculation is carried out during a few cycles to reach the steady state. The velocity in the cavity and outside the cavity is the main output of the model. This method gives information about the distribution of the velocity during the entire cycle, either in suck or blow phases.

The comparison of maximum output jet velocity on the last cycle, with the test campaign measurements enabled the validation of the CFD modelling.

The output jet velocity reach is maximum at the phase $\pi + 10°$ of the cycle. The velocity distribution at that time is shown on figure 3.

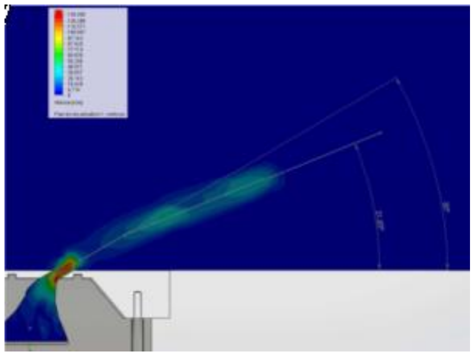

Figure 3: Output jet velocity distribution, at maximum velocity of the cycle

1.4 System modelling approach

A system modelling has been built to represent and predict the behavior of the entire mechanism. A lumped element approach is considered, allowing the simplified representation of piezoelectric and fluidic parts. The scheme of the lumped element model is available on Figure 4. Each element, the membrane, the cavity, and the nozzle, is assumed to be composed of spring, mass and damper.

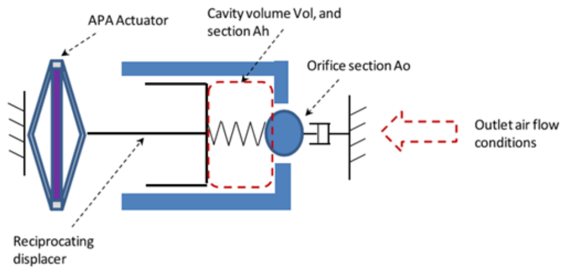

Figure 4: System modelling of the transducer using Mass, Spring, Damper representation

The modelling of the cavity and nozzle is based on the Helmholtz resonance. The main characteristics of the system are taken as parameters of the modelling. The main input are the geometric parameters of the fluidic components, the piezoelectric characteristics of the membrane, and the applied voltage. The outputs are the membrane displacement, output jet velocity, resonance frequency and also the power supply required to drive the actuator. This last data allows to choose an electronic device enables to manage the SJA.

An overview of the system modelling results are available on Figure 5 and Figure 6. For two different sets of the fluidic components' parameters, the membrane displacement and output jet velocity are plotted. The graphs show that the actuation frequency depends on the geometry of the SJA as the configuration a reach its maximum velocity at 1730Hz and configuration b at 1500Hz.

Then there is an optimum in terms of coupling between the piezoelectric component and the fluidic part to find by adjusting the fluidic parameters for a given piezoelectric actuator.

Actually, the configuration a has a lower actuator displacement than in configuration but the jet velocity is higher.

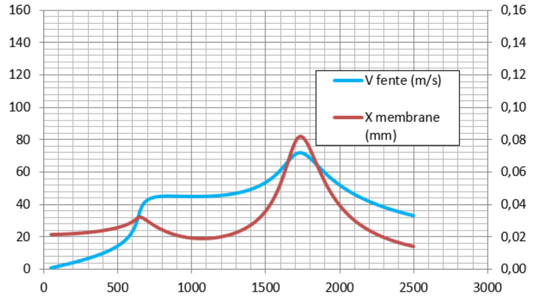

Figure 5: System modelling results for configuration a

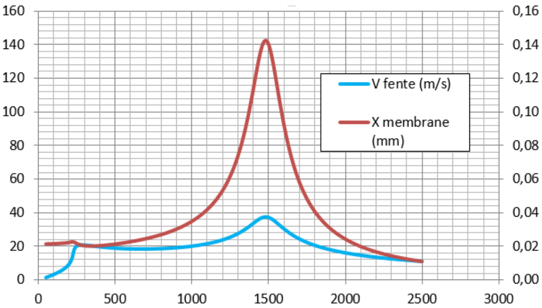

Figure 6: System modelling results for configuration b

1.5 Improving modelling correlations

Comparison between CFD, system modelling and test measurements has been performed to validate the correlation between the calculation and real behavior of the SJA. Even the SJA modelling tends to overestimate the jet velocity, the variation of the velocity with the SJA sensitive parameters is representative. Finally, this model is accurate to predict the evolution of the actuator's performance when the design is modified.

Further studies will allow to improve the jet velocity using the system modelling. The identification of the operating point, and other outputs as power consumption and power supply, allow the definition of the associated electronic device. That also enable to work on the design in aim at reducing the consumption of the SJA.

2. FLOCOS PROJECT – THE DEVELOPMENT OF SJA DRIVE ELECTRONICS "SADS"

In the frame of the EU H2020 project FloCoS, a flow control actuator driving system considering the specific requirements of piezoelectrically driven Synthetic Jet Actuators is designed and developed.

2.1. Dimensioning

The main characteristics of the SADS are the following:

- Be able to drive up to 96 actuators
- Excitation up to 2500Hz
- Actuator capacitance up to 200nF
- Output voltage range up to 200V pk-pk

This leads to the following needs:

- Up to 250mA per channel
- A margined power of 20W / channel (Eq. 1)

$$P = I_P * \frac{V_{DD} - V_{SS}}{\pi} = 15.9W$$

$$With \begin{cases} I_P = 250mA \\ V_{DD} = 200V \\ V_{SS} = 0V \end{cases} \qquad (1)$$

The system needs both to work at the actuator resonance frequency, or at a larger frequency bandwidth for a fully characterisation of the SJA.

Firstly, a trade-off has been made between linear and switching amplifying technology. Both technologies are part of CTEC knowledge. Switching technology could be addressed with class D PWM amplifier, or resonant amplifier. The resonant technic is not well adapted to the Flocos project, because the requirement also demands the capability to work on a wide bandwidth. One can see on Fig 7 a comparison in terms of power losses vs amplifier channel current:

Amplifier current	Switching technology power loss	Linear technology power losses
50mA	~5W	3.5W
100mA	~5W	7W
200mA	~5.5W	~14W
400mA	~6W	~28W

Figure 7: Power losses vs amplifier technology and output current

A switching amplifier has the advantage not losing more power when the output current increases. See [9] for more details about the switching amplifier technology.
Problem is this switching technology is bad in terms of EMC concerns, and these problems increases with the length of the connections between the amplifier and the actuators.

This problem is critical on Wind tunnel situation, with the driving electronics outside the test area, where the cable length could be more than 100meters.
Plus, the voltage and current need to be monitored by the driving electronics, as important results during tests. The noise induced by a switching technology is a strong limitation for this application. Additionally, the bandwidth of such solution is lower due to the output filtering part which is calculated in regard of the signal to noise performances, i.e. the lowest the bandwidth, the better noise signal to

ratio. In consequence, a linear amplifier technology similar to [10] has been chosen and adapted to this specific power and application.

2.2. Architecture

The SADS is composed of two electronic racks, who can drive up to 48 actuators each.
A master / slave structure is chosen between two of these racks to reach up to 96 channels.

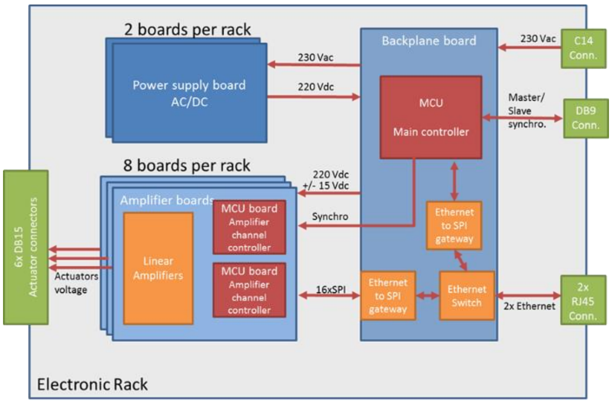

Figure 8: Overall architecture of the SADS

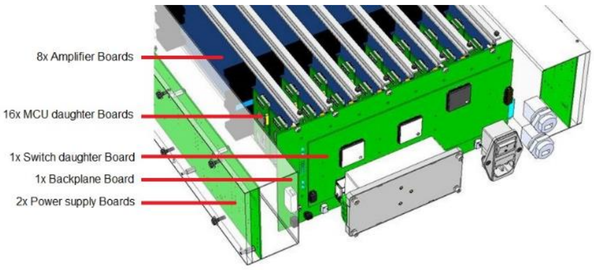

Figure 9: Electronic rack integration of SADS

The SADS's electronic rack is composed of:

- 2 power supply boards

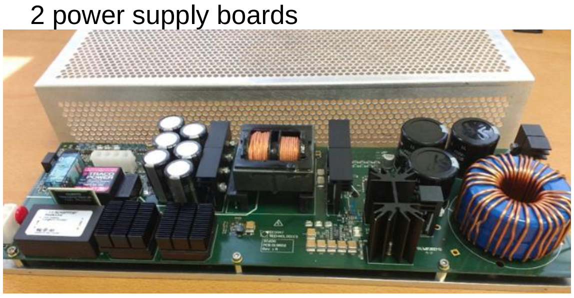

Figure 10: Power supply board, shielding removed

Two 600W supplies, from mains supply (110VAC or 230VAC) to 210VDC output, for the amplifiers are embedded. These power supplies include a PFC (Power Factor Correction) function and use an LLC resonant converter architecture. For more details about these techniques, see [11].

- 8 amplifier boards

Figure 11: 8 Amplifier board

Each amplifier board have 6 independent linear amplifier channels. A voltage and current feedback for monitoring and driving are added (see control loop mode). 2 MCU daughter boards emplacements, for driving and monitoring purpose are integrated.

- 16 MCU daughter boards

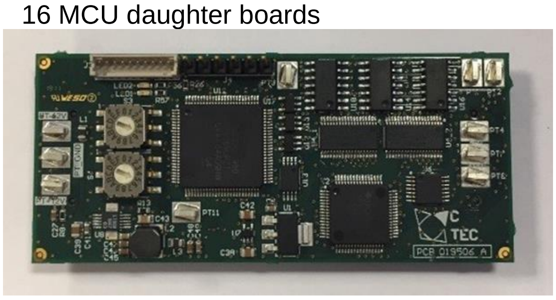

Figure 12: MCU board

MCU daughter boards are mounted on the amplifier boards and include all the digital functions needed for each channel: ADC, DAC, microcontroller, current/voltage phase detection. They can drive 3 amplifier channels. Each one can generate an independent sinus command signal, or an amplitude modulated signal. Thanks to the voltage / current phase detection, MCU boards can work as MPPT (Maximum Power Point Tracker) and generate an optimal driving command to each actuator.

This board can register the voltage and current measurement during time lap and let them be downloaded later.
All these functionalities are independently configured through the TCP/IP network, to be internally generated, or asserted to a common one, generated by the master rack.

- 1 backplane board

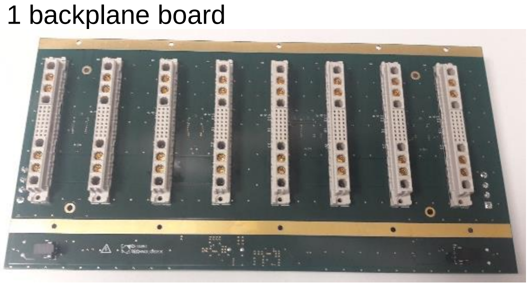

Figure 13: Backplane board

This board contains plugin slots for the Amplifier boards, so they can be quickly replaceable and interchangeable. This board also includes low voltage generation (+/-11VDC) for numerous digital components and analogic functions. This board is mainly a passive part. The active part of the backplane board is the Switch daughter board

- 1 switch daughter board

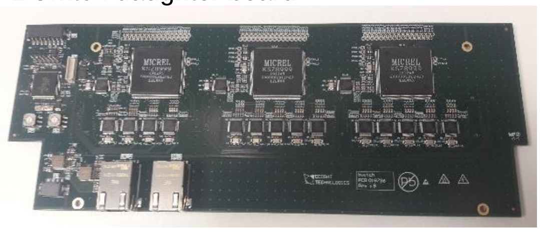

Figure 14: Switch board

Installed on the backplane board, this daughter board integrates all the active functions of the backplane board. This board includes all the switches for the TCP/IP network, and all the Ethernet controllers for each MCU boards. There are additional ports, to communicate between master and slave(s) rack(s), and outside the system (for the client supervisor). This communication solution is proposed in regard of the testing phase in the wind tunnel, where the distance between the rack and the supervisor could be long.
The main microcontroller is located on this board, to generate any common signals to all the channels: A sinus command, a modulation signal, and a trigger to allow a synchronous acquisition of voltage and current measurements. If configured for a slave rack, this microcontroller only repeats any signal from the master rack one.

2.3. Operating modes of the SADS

The SADS system is designed to be as flexible as possible, to be used for any environment.
Any channel can be individually configured to work on a different mode, and with different inputs.

- Open loop mode

In this mode, the amplifier channel output is set to a configured sinus signal (frequency and amplitude), and a sinus amplitude modulation (frequency and amplitude)

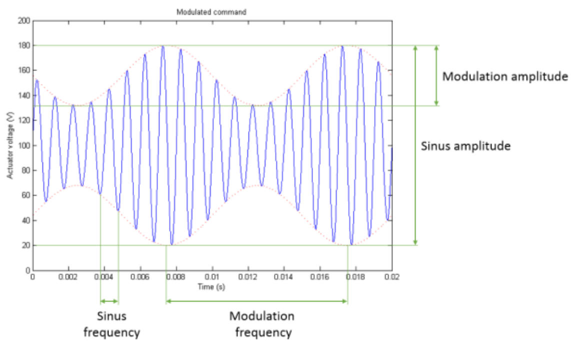

Figure 15: configuration parameters for the actuator command generation

For each channel, these two signals (sinus and modulation) can be configured separately. For a synchronized behaviour between channels, another set of signals is generated by the Switch daughter board on the master rack, and each channel can use these common signals or their own ones.

- Closed loop mode

In this mode, the command frequency is automatically asserted to get each actuator it's maximum efficiency.
This mode uses a MPPT (Maximum Power Point Tracking) algorithm. This algorithm constantly makes small frequency increases or decreases, in order to find the minimum phase between the voltage and the current.

A trade off was realised about the choice of the technique to assure the monitoring of the mechanical resonance frequency. The main techniques are based on US transducer solution where the need is very similar, but at a higher resonance frequency.
This method, using only voltage and current measurement, avoid the need of any sensor on the mechanism to work properly. This is a major advantage, considering the integration complexity and miniaturisation level of the SJA.

Fig 16 is an example of phase profile of an SJA. One can see there is multiple phase minimums, thus corresponds multiple resonance frequencies. In this case, a starting frequency must be set near the desired working frequency, prior starting the MPPT algorithm, who will converge to the nearest optimal working point.

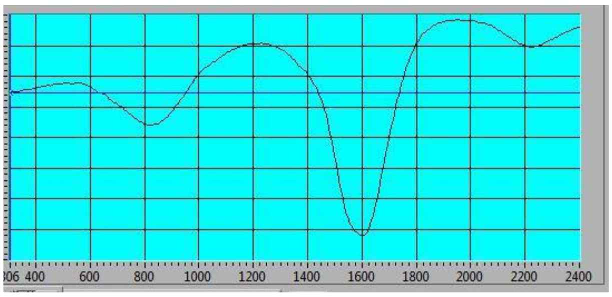

Figure 16: Voltage / Current phase profile of a SJA actuator

In order to maximize the performance of the AFC actuators, a dedicated Maximum Power Point Tracking (MPPT) control algorithm is integrated to get an optimized electrical drive signal for every individual actuator. For making measurement values available which will be used for MPPT control of the actuator, each voltage and current is internally monitored (and recorded for external study). The MPPT algorithm is looking for the minimum phase between the voltage and the current to find the optimum working point.

3. TOWARD A NEXT GENERATION OF SJA

The SYNJET3C project is expected to provide design optimisation methods based on enhanced modelling tools providing simulation results for both quiescent air conditions, and cross flow air conditions on SJA performances. The ongoing wind tunnel test at ONERA for cross flow air conditions (not presented yet at this stage of the project) shall allow to refine the modelling approach in the design process of an SJA actuator.
As the outcome from this project, a new generation SJA scale model shall be designed, manufactured and tested, making use of the modelling method developed, and based on CTEC APA® piezoelectric actuator technology. This new design of a scale model shall benefit from both knowhow from FRANHOFER and ONERA, in terms of targeted performances, integration, and test methods, as well as from CTEC heritage in the design and manufacturing of long lifetime, and reliable piezoelectric actuators, for aerospace domain.

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