FIRST WORKSHOP

Aerodynamic Design and System Development of Synthetic Jet Actuation for Flow Control at the Engine/Wing Junction

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2ND GENERATION ACTIVE WING

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Presenter:
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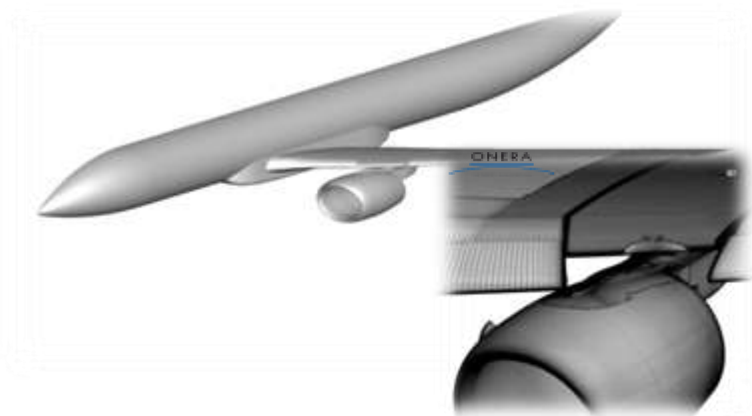
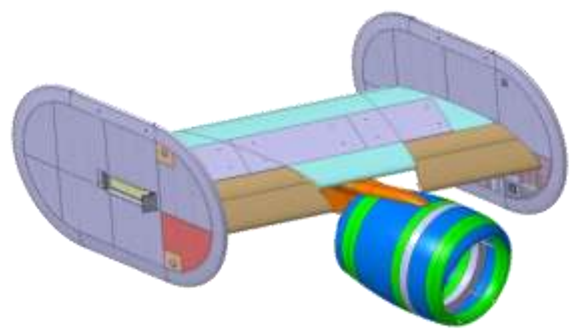
Outline of presentation

- Background
- Synthetic Jet Actuator (SJA) concept
- High frequency SJAs for flow control (example)
- Aerodynamic design of SJA system for Wing-Pylon-Nacelle configuration
- Aerodynamic modelling of SJAs
- Aerodynamic analysis of SJAs
- System development
- Development of SJAs
- Development of High Voltage Amplifier (HVA)unit
- Conclusions

Background

- Scope:
- Application of **Synthetic Jet Actuators (SJAs)** for Active Control of Flow around Wing-Pylon-Nacelle configuration
- **Motivation**: Active Flow Control as Enabler for UHBR Turbofans





- Objectives:
  - To mature Active Flow Control technologies: suppress nacelle-wake separation by Pulsed Jet and **Synthetic Jet Actuation**
  - To investigate performance of SJAs by aerodynamic simulations
  - To develop system integration concepts accounting for real aircraft constraint & requirements
  - To demonstrate technology in large scale WT model

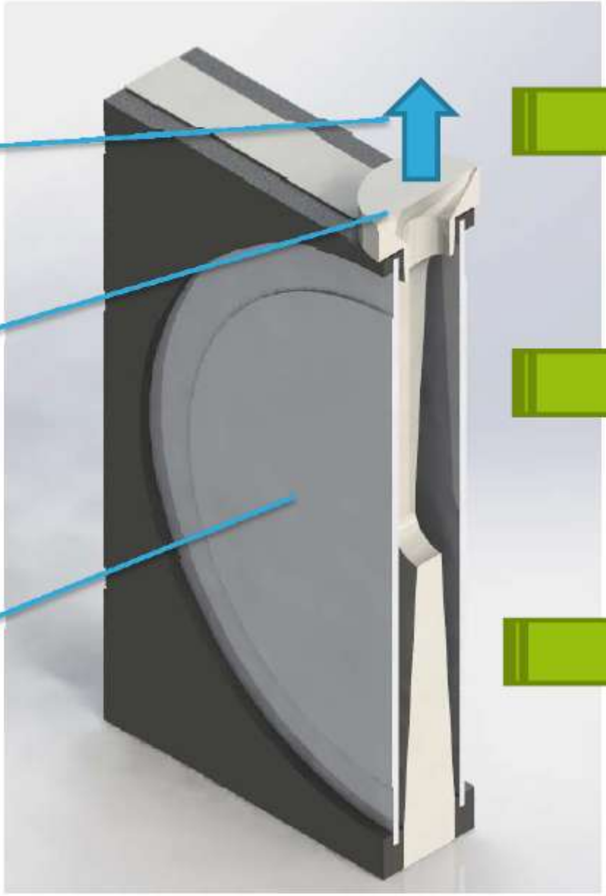
Synthetic Jet Actuator (SJA) concept

First concept studies with slot geometry

<u>Exit velocity:</u>
- Targeted value: 200 m/s

<u>Exit geometry:</u>
- Slot
- 10 x 0.5 mm²

<u>Transducer:</u>
- single or dual transducer concept
- f = 2 kHz



Performance needs to be increased
→ Change of transducer size

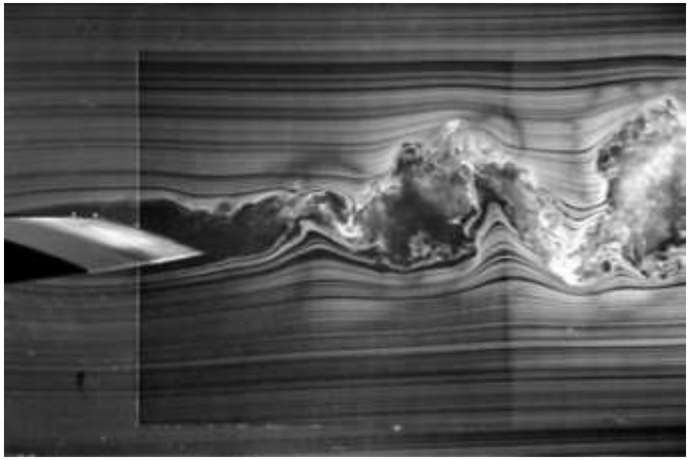
Innovative nozzle design necessary

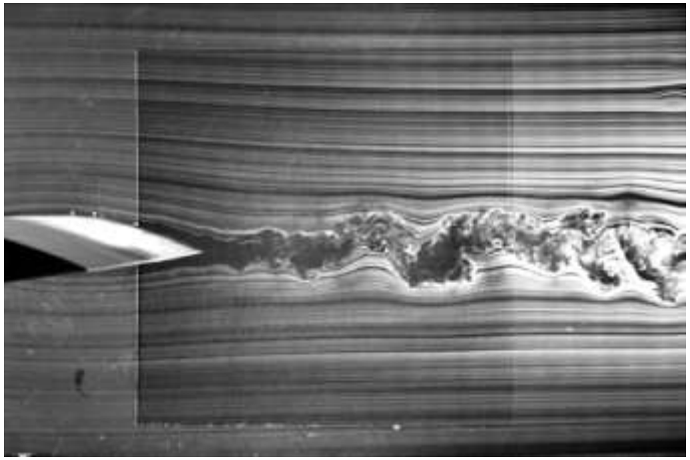
Single transducer concepts for increased robusteness

High frequency SJA for flow control

- Objective: to reattach separated flow, to increase lift and to decrease drag

- Example from recent literature (Goodfellow, AIAA journal, 2013):
  - Application high frequency SJAs for flow control to 2D flow
  - Re-attachment of flow around a NACA 0025 airfoil (at a chord-based Reynolds number of 100,000 and an angle of attack of 5 degrees)





uncontrolled

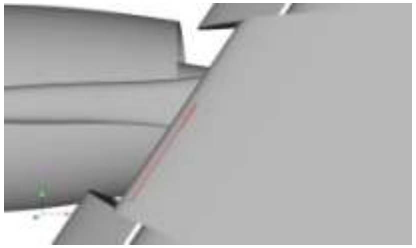
$C_\mu = 0.3\%$

- Design parameters:
  - Excitation frequency, Excitation location, Excitation amplitude, Number of excitation jets
  - Control parameter: Dimensionless momentum coefficient C_μ

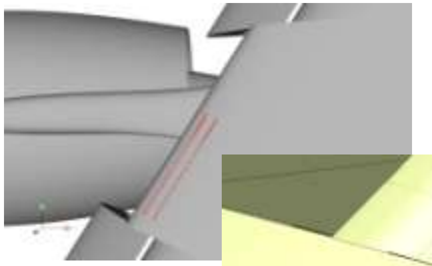
Aerodynamic design for SJA system in WT model

Positioning of SJA slots

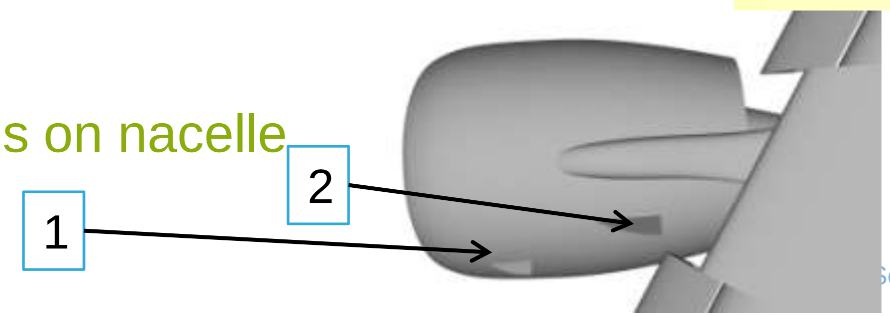
- 85 of actuators placed 0.021%c from the leading edge between the inboard and outboard slat
- 2nd row is placed 0.021%c downstream of 1st row



- Length 0.83 m
- Circular area outlet 5mm^2
- Pitch angle 30deg

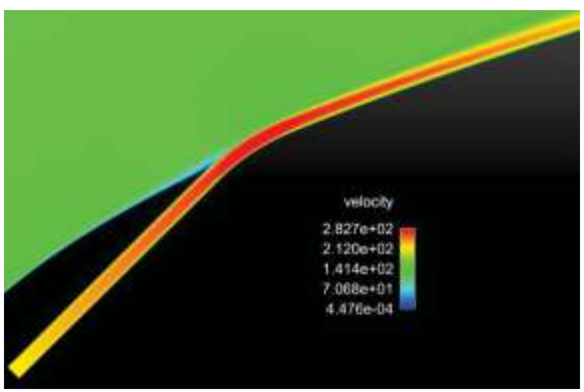


Two strake positions on nacelle

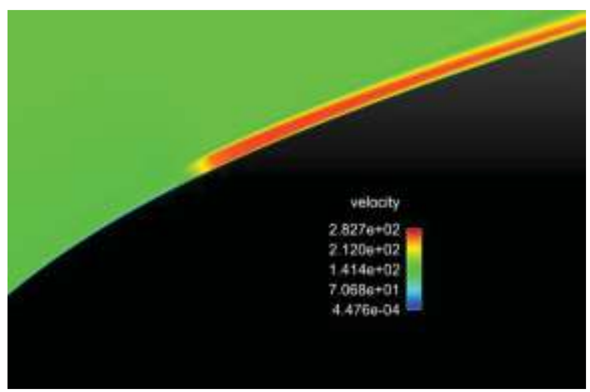


Aerodynamic modeling of SJA

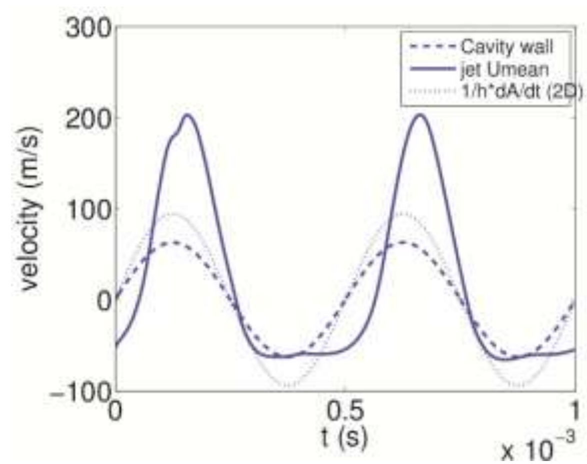
- 3D steady computations using steady model of SJA
- with averaged forcing conditions for momentum, energy, K and ω
- same computational effort as for steady RANS
- same mesh as for steady clean RANS can be used (no slot or cavity)
- Resolved 2D URANS (2000Hz) with pumping cavity
- for calibration of SJA forcing model
- note the asymmetric outlet velocity in time



Resolved slot jet

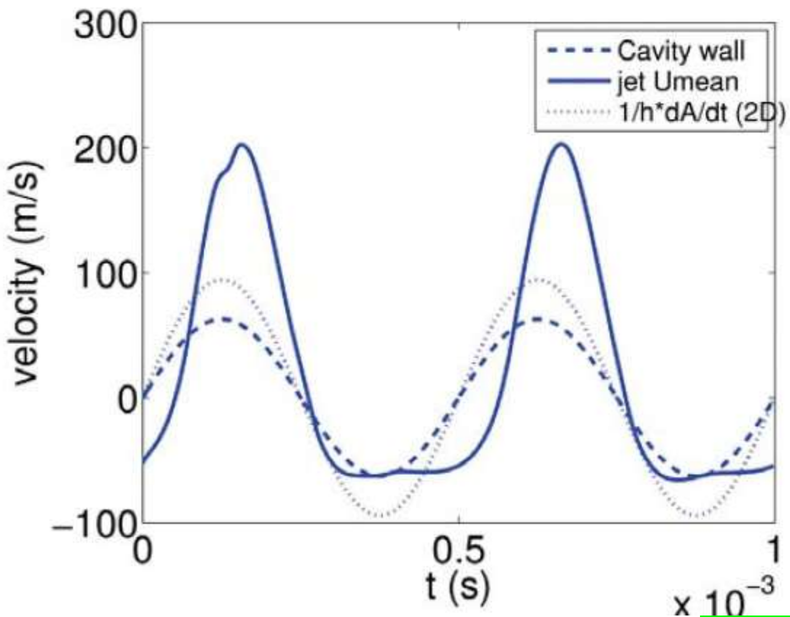


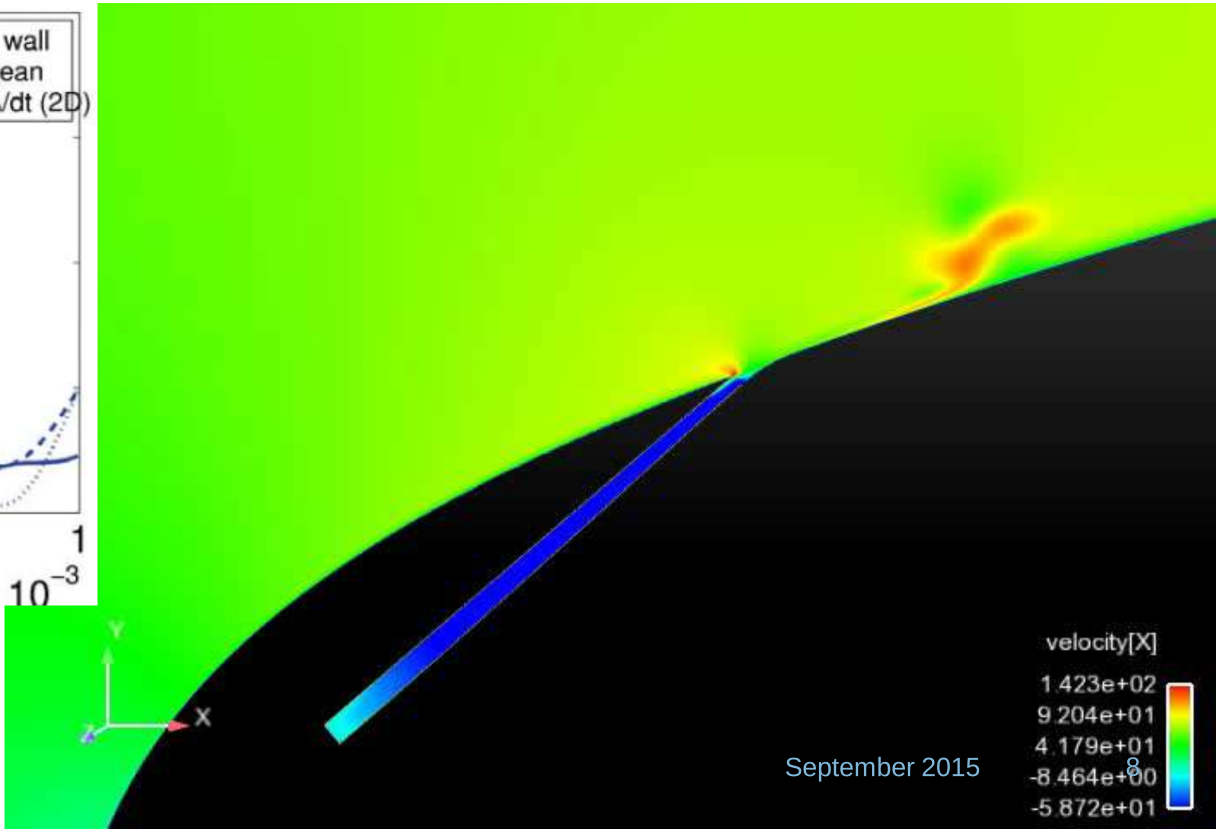
Forced jet



2D synthetic jet simulation

- Extracting/contracting mesh cavity
- Slot exit width: 0.5 mm
- Frequency 2000 Hz
- Umax = 200 m/s





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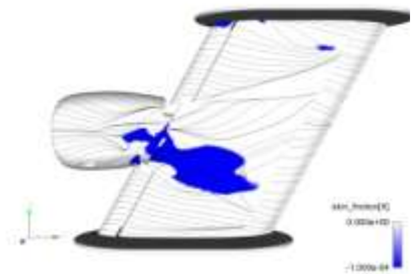
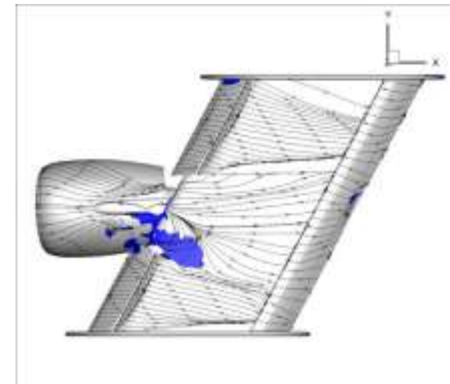
CFD results

FOI results

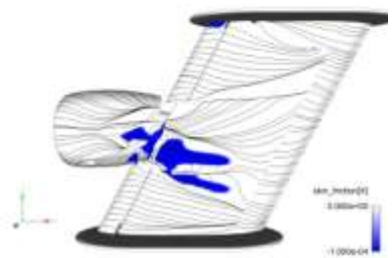
VZLU results

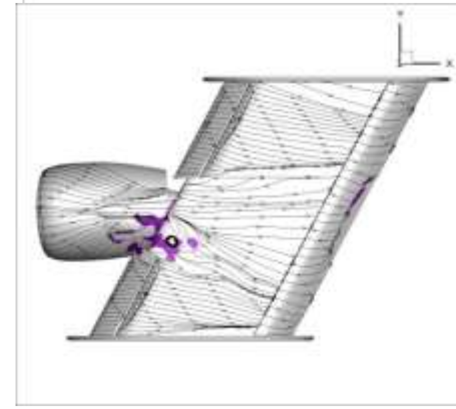
Baseline and strake



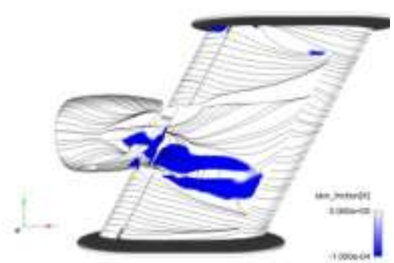


With two rows of SJAs





With one row of SJAs

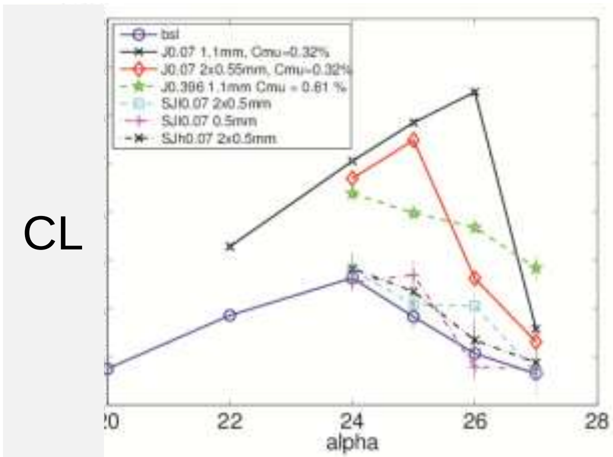


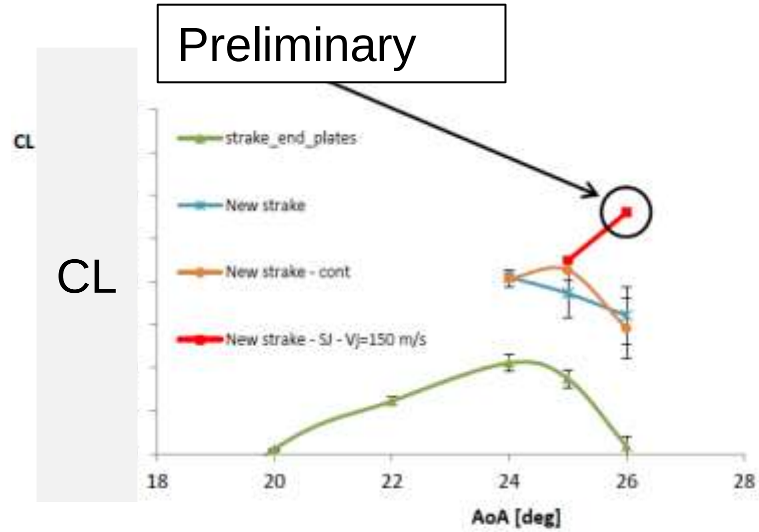
Strake Pos. 1
AoA – 27 degr
Ujet 200m/s
f= 2000 Hz

Strake Pos. 2
AoA – 26 degr
Ujet 150m/s
f= 100 Hz

CFD results

CL vs. AoA





Strake Pos. 1
Ujet 200m/s
f= 2000 Hz

Strake Pos. 2
Ujet 150m/s
f= 100 Hz

Conclusions:

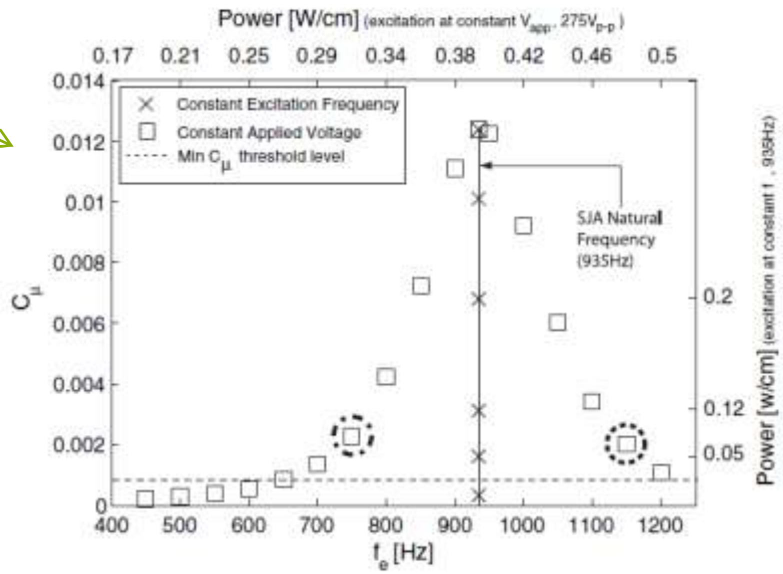
- Slight improvement of lift is observed
- No unsteady RANS results available for f=2000Hz

Aerodynamic analysis

Momentum coefficient

- For synthetic jets excitation amplitude is commonly characterized by the momentum coefficient
- From (Goodfellow, AIAA J 2013.)

$$C_\mu = \frac{DC \times \rho_j S_j U_{peak}^2}{S_{ref} \rho_\infty U_\infty^2 / 2}$$



- A substantial decrease in drag is attained only when synthetic jet actuation is applied at a sufficiently high amplitude
- Momentum coefficient should be larger than 0.3% (referred as Goodfellow threshold)

Aerodynamic analysis

Momentum coefficient for WT model

- Active Control of Flow around Wing-Pylon-Nacelle configuration
- Assumptions: DC=0.5; $\rho_j = \rho_\infty$ $C_\mu = \frac{DC \times \rho_j S_j U_{peak}^2}{S_{ref}\rho_\infty U_\infty^2 / 2} = \frac{S_j U_{peak}^2}{S_{ref} U_\infty^2}$

$S_j = \text{ number of slots x area slot} = 80 * 5 * 10^{-6} \text{ m}^2$

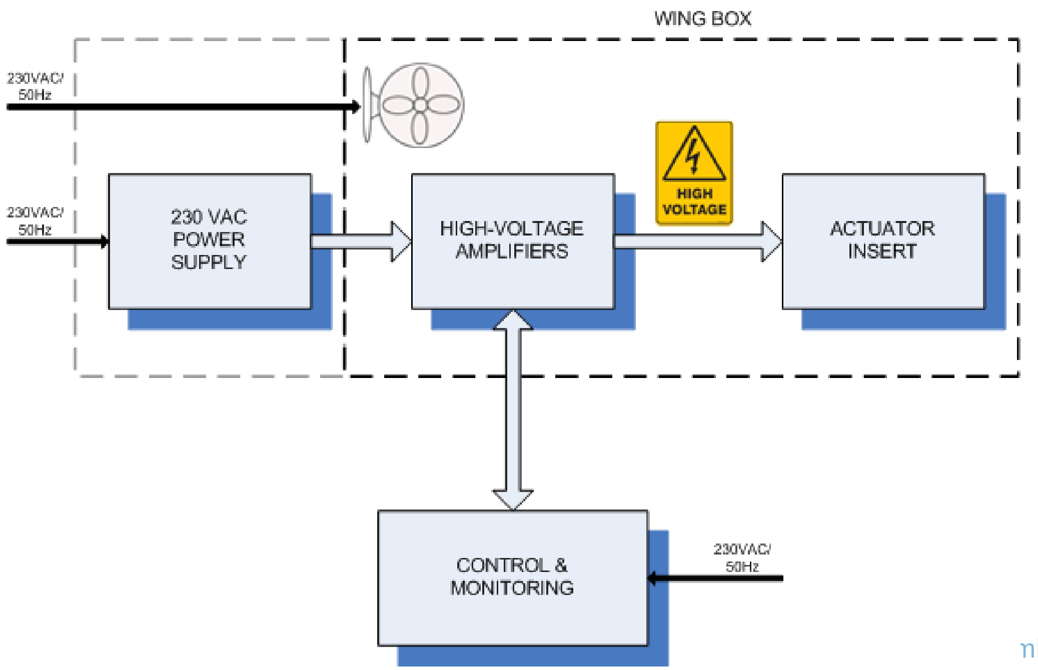
$S_{ref} >= 3 \text{ m}^2$ $U_{peak} = 200 \text{ m/s}$ and $U_\infty = 51 \text{ m/s}$

- Then $C_\mu \approx 0.2\%$ is just below the Goodfellow threshold for $U_{peak} = 200 \text{ m/s}$
- This value is much lower than the threshold for Pulsed Jet Actuators (requires 1.76 %)

System development

Active flow control by means SJA's requires:

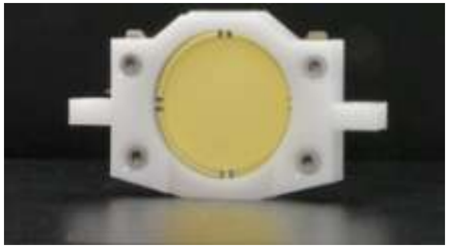
1. **Development of stackable array of SJA's**
2. **Development of High-Voltage amplifier unit to drive SJA's**
3. Control system
4. Several sensors to measure performance of SJAs
5. **Development of specific insert in WT model**

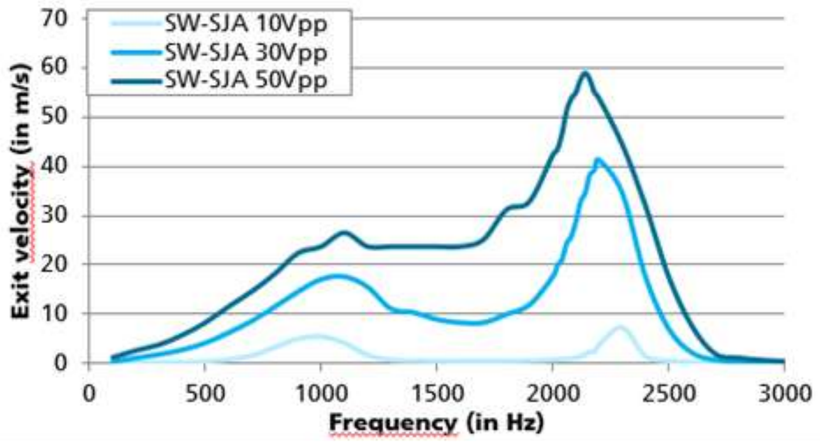


Development of SJAs

Stackable Synthetic Jet Actuators

- Designed for very compact integration
- Models with single and dual transducers available



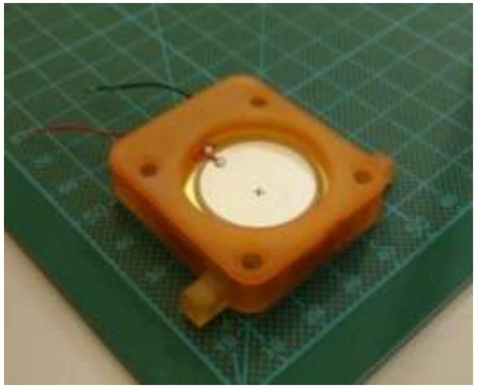


Characterization results (method: aneometry)

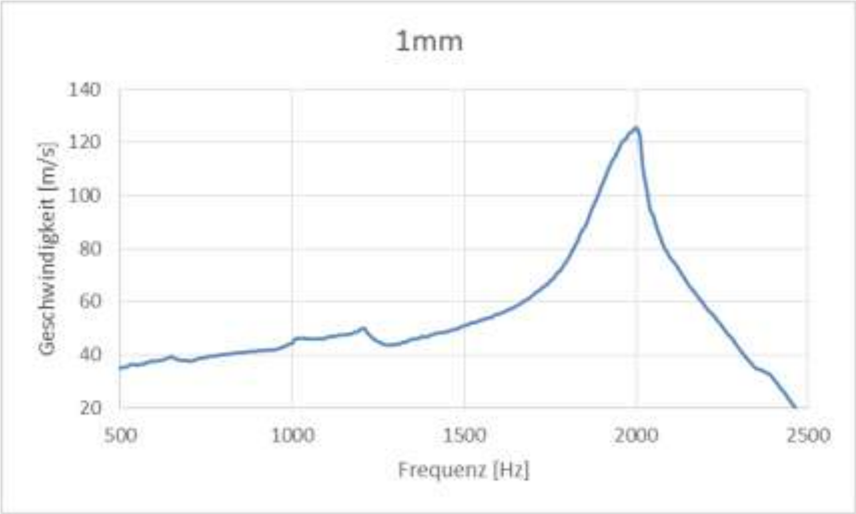
Development of SJAs

High Power Synthetic Jet Actuators

- Designed for increased power density
- Compact integration is possible
- Different exit geometries available



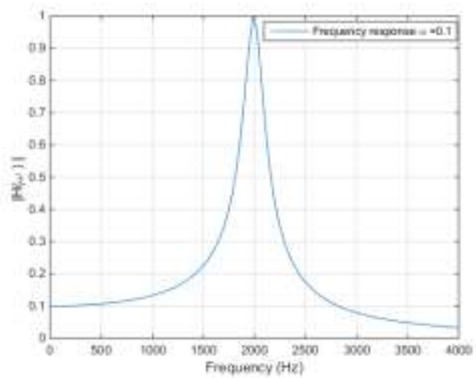
SJA Prototype

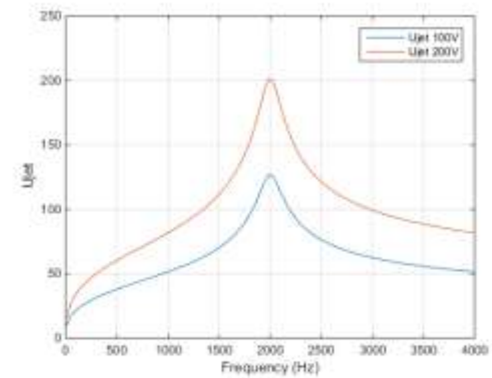


Development of SJA system

- Peak velocity can be estimated by the following formula

$$u_{peak} = \sqrt[3]{\frac{\eta \omega c V^2}{a \rho} |H(\omega)|}$$





Assume $f = 2000$ Hz ($\omega = 2\pi f$), $c = 200$ nF, $V = 200$ Volt, slot area $a = 0.000005$, $\rho = 1.22$ kg/m^3.

Then, the exit peak velocity u_{peak} at the nozzle becomes 200 m/s.

- Challenge 1: To attain an exit velocity of 200 m/s the applied voltage has to be at least 200 Volt
- Challenge 2: To pass the Goodfellow threshold (the momentum coefficient should be larger than 0.3%)
- Challenge 3: To develop an integrated stack of equivalent actuators with the same resonant frequency

Development High Voltage Amplifier (HVA) unit

- Market survey for drivers of piezo transducers
- Most suitable HVA: **PiezoDrive MX200**
  - Can drive 6 SJAs @ 100 Vpp, 2 kHz
  - Can drive 1 SJA @ 200 Vpp, 2kHz
  - Acceptable size
  - Internal HV power supply
  - Forced air flow – fan (weak point)

Specifications	
Power Supply	24V (18V to 36V)
Voltage Range	+100V, +150V, or +200 V
Peak Current	1 Amp
RMS Current	550 mA, 330 mA, 220 mA
Power Bandwidth	106 kHz (180 Vp-p)
Signal Bandwidth	200 kHz (100nF Load)
Slew Rate	60 V/us
Gain	20 V/V
Input Impedance	33 $k\Omega$ (In+), 1.6 $k\Omega$ (In-)
Input Offset	$\pm$5 mV
Load	Unlimited
Output Noise	<100 uV RMS (10Hz to 10kHz)
Protection	Short-circuit, average current, and under-voltage protection
Quiescent Current	0.3 A (30 mA in Shutdown)
Dimensions	80 x 46 x 40 mm (L x W x H)
Environment	-40 to 60°C (-40 to 140°F) Non-condensing humidity
Weight	95 g

HVA unit at system level

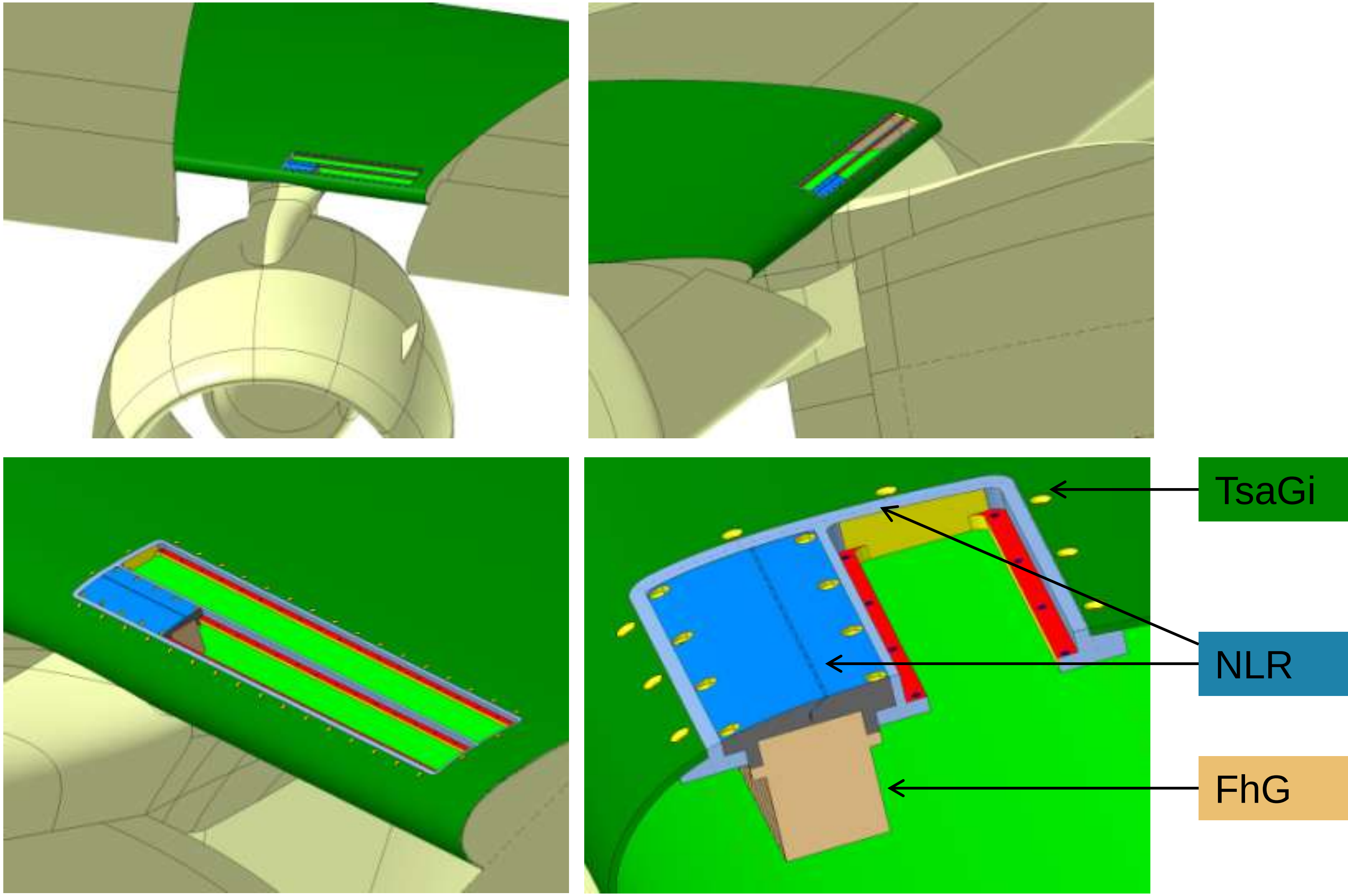
# of SJA	Required V_pp	#SJAs/ (Amlpifier)	#Amplifiers	Estimated power (W)	Estimated mass amplifiers (kg)	Estimated volume amplifiers (liters)
85	100	5	17	600	2	3
85	150	2	43	1500	5	7
85	200	1	85	3000	9	13
169	100	5	34	1200	4	6
169	150	2	85	3000	9	13
169	200	1	169	6000	17	26

Amplifiers have to embedded in standard subracks

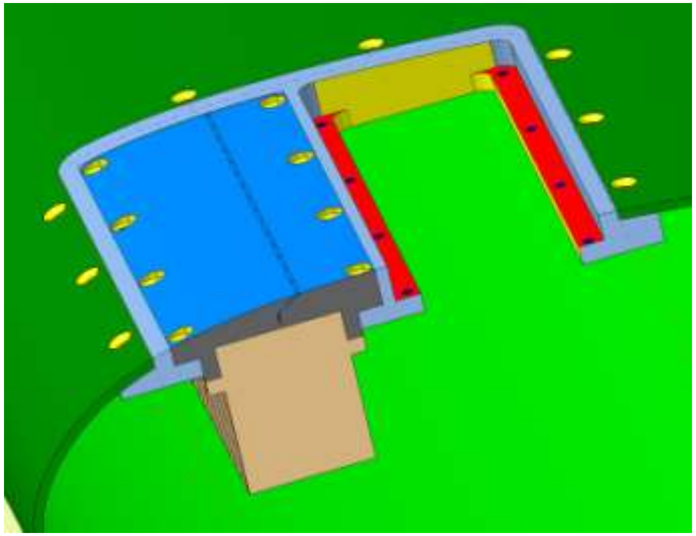
Mounting in the wing box

Schroff 19”/3U subrack

Development of insert in WT model (NLR)

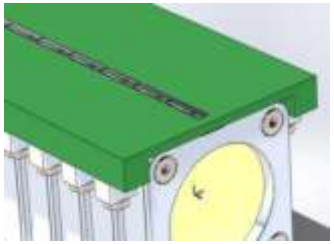


Development of insert in WT model



Proposed insert consists of two main parts:

- Frame (NLR)
- Set of actuators with top cover (FhG)



Frame:

- Aluminium alloy - one or two rows
- Mounted separately in the wing box
- Also reinforces the wing box
- Flat top surface ⇨ mounting from <u>below</u>
- *Mechanical interface with WT hardware*

Actuator set:

- Aluminum top cover
- Individual actuators can be replaced easily from the <u>top</u> side

Conclusions

- Aerodynamic analysis and CFD simulations:
  - No unsteady CFD results available for f=2000Hz
  - 3D steady EARSM of FOI does not show benefits of SJAs
  - 3D steady EARSM code has not been validated for unsteady jet calculations (only calibrated against 2D unsteady calculations)
  - 3D unsteady code of VZLU is only applied for f=100Hz
  - Challenge: The pass of Goodfellow threshold (momentum coefficient should be larger than 0.3%) requires exit jet velocities of 200 m/s

- Development of SJAs
  - Jet velocity of presently available SJAs is too low
  - SJAs have to be driven at resonant frequency (present stack shows scattering of resonant frequencies)
  - The amount of energy provided by one SJA is limited (~~ 0.001 Joule)
  - Challenge: To attain SJAs with exit velocity of 200 m/s (requires use of High Voltage Amplifiers)
  - Challenge: To develop an integrated stack of equivalent actuators with the same resonant frequency

Conclusions

- Development of High Voltage Amplifiers
  - Challenge: To attain an exit velocity of 200 m/s the applied voltage has to be at least 200 Volt
  - This requires the use of one PiezoDrive MX200 for each SJA (total 85)
  - Challenge: The integration of 85 MX200 drives on Printed circuit boards and the embedding in subracks (8 subracks are required)
  - Commercial available MX200 PiezoDrives are bulky (too heavy for installation in real aircraft)

- Design of insert
  - SJA system can be replaced from top side

Thank you !

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