Local correlations for flap gap oscillatory blowing active flow control technology

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Abstract: *Active technology for oscillatory blowing in the flap gap has been tested at INCAS subsonic wind tunnel in order to evaluate this technology for usage in high lift systems with active flow control. The main goal for this investigation was to validate TRL level 4 for this technology and to extend towards flight testing. CFD analysis was performed in order to identify local correlations with experimental data and to better formulate a design criteria so that a maximum increase in lift is possible under given geometrical constraints. Reference to a proposed metric for noise evaluation is also given. This includes basic 2D flow cases and also 2.5D configurations. In 2.5D test cases this work has been extended so that the proposed system may be selected as a mature technology in the JTI Clean Sky, Smart Fixed Wing Aircraft ITD. Complex post-processing of the experimental and CFD data was mainly oriented towards system efficiency and TRL evaluation for this active technology.*

Key Words: active flow control, experimental fluid mechanics, oscillatory blowing, aeroacoustics.

1. INTRODUCTION

Active flow control (AFC), based on oscillatory blowing in the flap gap, was consider as a promising technology able to deliver a new generation of high lift systems, as already introduced in specific investigations [1, 2]. It was demonstrated in the wind tunnel that separation could be limited by oscillatory blowing and specific systems have been successfully used in complex setups [3,4].

A set of wind tunnel test in AVERT project [5] demonstrated the potential of this technology, mainly with respect to current state of the art capabilities in fluidic actuators and global system design. Major goal of the investigations is related to the possibility of scaling AFC system using oscillatory blowing, so that this technology could be developed to a higher TRL level and implemented in a new generation of aircrafts.

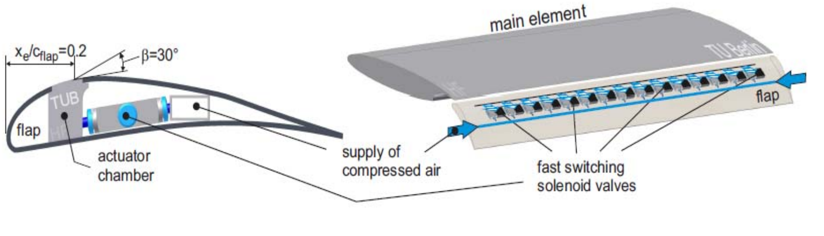

Fig. 1 – AFC using oscillatory blowing

The target configuration for the analysis is a single slotted trailing edge flaps or plain flap respectively, in both 2D and 2.5D configuration. The models are equipped with a specially designed excitation mechanism that is capable of producing a pulsed wall jet with high jet velocities using compressed air and fast switching solenoid valves [3,4] (Fig. 1).

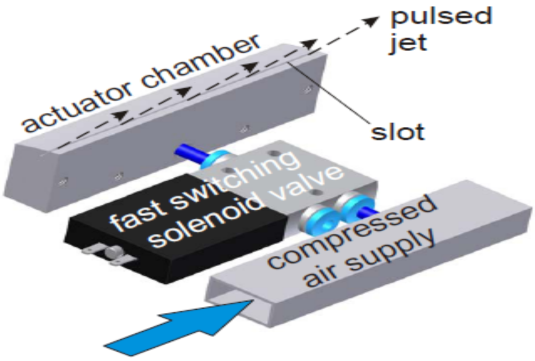

Fig. 2 – AFC system architecture

The system architecture to be implemented in the flap is presented in Fig. 2. This design, proposed by TU Berlin and evaluated in several other testing campaigns [4] was selected for further investigation in AVERT project. The results from the test campaign include detailed measurements from a six- component wind tunnel balance and pressure sensors readings.

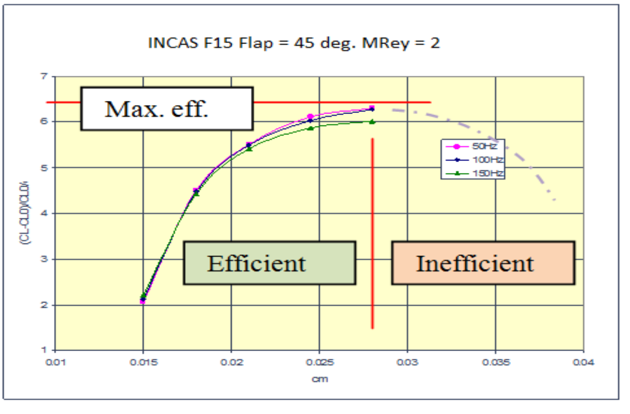

Fig. 3 – AFC efficiency in 2D configurations

For the system under investigation, efficiency is considered based on the global effect of the oscillatory blowing system as presented in Fig. 3. Here one might expect that the system is limited with respect to the global lift, at a reasonable mass flow rate that can be scaled afterwards for real flight.

2. EXPERIMENTAL RESULTS FOR AFC

Following the experiments for both 2D and 2.5D configurations, data recorded has been post-processed in order to evaluate AFC and oscillatory blowing technology for high lift system. There were three flap configurations, with different flow patterns, also with different response to the AFC technology.

Tests were performed in order to identify potential benefit of the AFC on high lift system. From the pressure distribution in Fig. 4, it is easy to conclude that we have one configuration with strong separation on the flap (45 deg.) and two configurations with a relative attached flow (40 and 49 deg.). They have different response to the AFC (Fig. 5, 6 and 7), with relative limited influence in the operating conditions (pressure from 4 to 8 bar and frequency from 25 to 200 Hz).

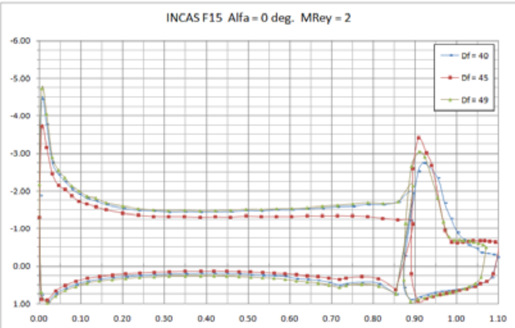

Fig. 4 – AFC, Flap 40, AoA = 0 deg.

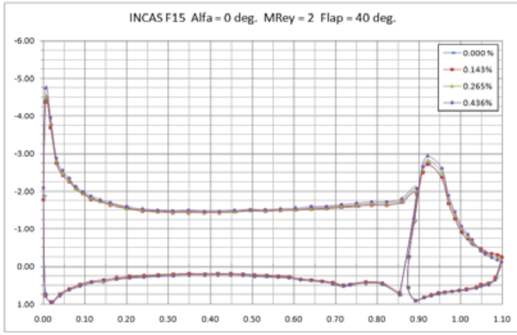

Fig. 5 – AFC, Flap 40, AoA = 0 deg.

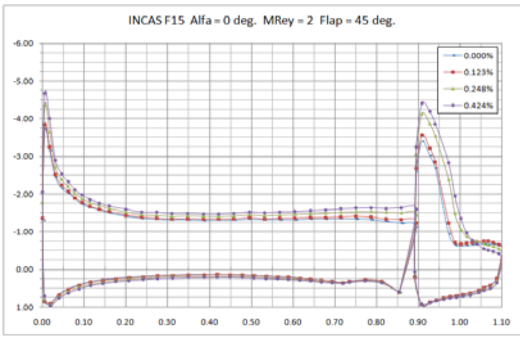

Fig. 6 – AFC, Flap 45, AoA = 0 deg.

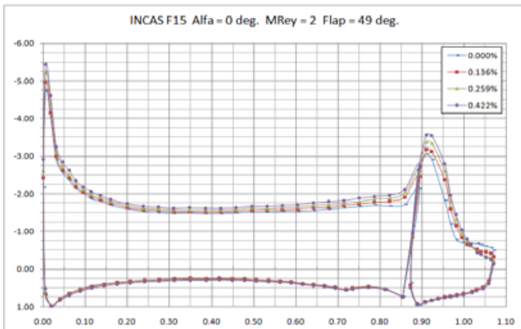

Fig. 7 – AFC, Flap 49, AoA = 0 deg.

At the same time AFC was investigated using laser visualization system in order to enable full characterization of the oscillatory blowing technology. Specific smoke-laser and luminescent oil paint were used for various regimes, as presented in Fig. 8 and 9.

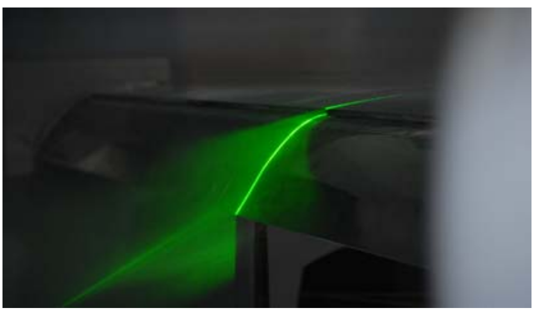

Fig. 8 – Laser visualization - Flap 45, no AFC

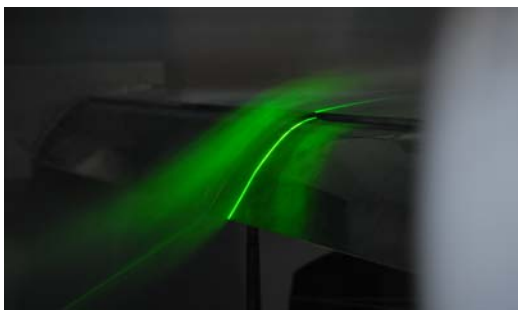

Fig. 9 – Laser visualization - Flap 45, with AFC

More results from the AVERT wind tunnel test campaign at INCAS Subsonic Wind Tunnel are presented in [6].

3. NUMERICAL SIMULATION FOR AFC

In order to evaluate the AFC technology for a new generation of high lift systems, numerical simulations have been performed to investigate the performance of the proposed geometries and architecture.

For example, the configuration with flap at 45 deg has been investigated in a 2D CFD analysis, where large separation is observed, as in Fig. 10. This flow pattern has also been investigated in the test campaign with oil paint, as presented in [6].

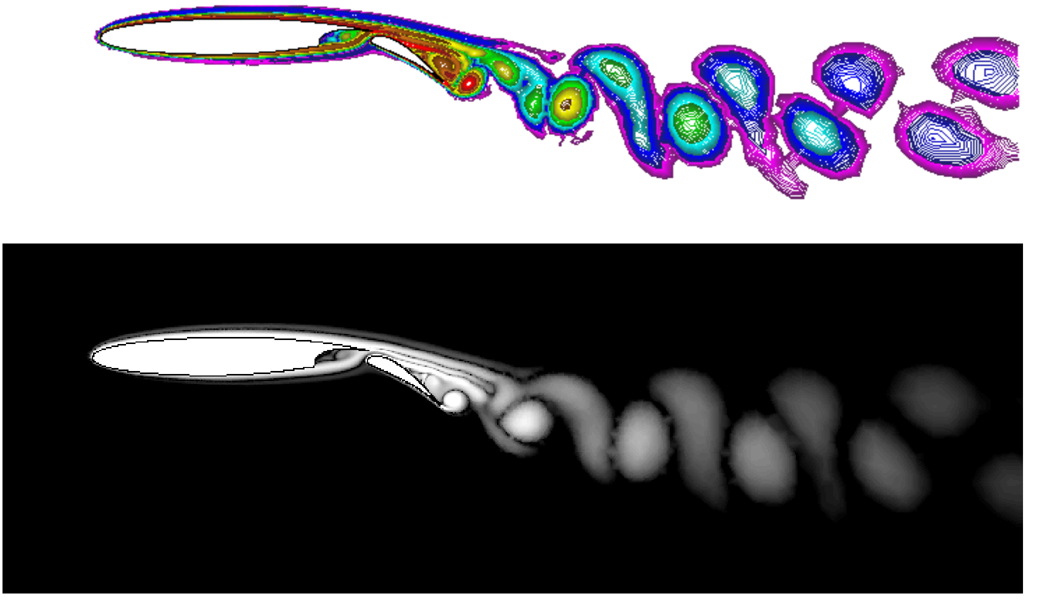

Fig. 10 –CFD analysis for AFC - flap = 45 deg. (iso-vorticity and numerical schlieren representations)

Data from CFD analysis, combined with pressure information from experimental data, are to be included in the aeroacoustic evaluation of the proposed noise metric.

4. AEROACOUSTIC EVALUATION FOR AFC

The airframe noise is an important noise source mainly for large aircraft in its landing and take off configuration. Also, the level of noise produced just by the passage of an airplane through the air, especially in its landing configuration, may only be a few decibels below the level of noise radiated from the engines. As a consequence, with respect to new designs for green aircraft, the main interest is for landing/take-off configurations and steep descent/climb maneuvers with reduced noise emission. Since we traditionally associate noise with the size and weight of the flying body, we can imagine an optimization process where one is interested to identify the optimum shape with respect to noise emissions giving the requested lift (here referred as High-Lift-Low-Noise concept)

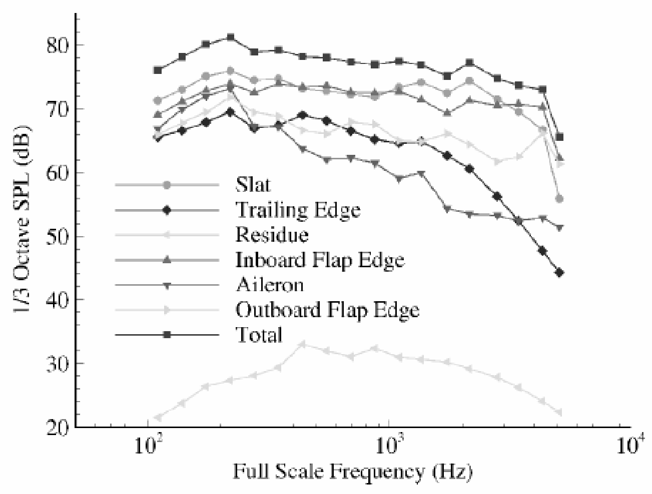

Fig. 11 – Source of airframe noise and reference values

In order to have an estimate of the noise sources localization and reference values in the case of a landing configuration, we present results from a specific analysis in Fig. 11 [7]. Here we emphasize that one might expect to identify airframe noise in the range of 1kHz and localized mainly with respect to the wing movables (leading edge and trailing edge) and slats. Therefore, one might expect that what we perceive as airframe noise is in fact a joint contribution of various noise sources with a specific contribution depending on the relative position with respect to a so called "clean" (or "cruise") global shape.

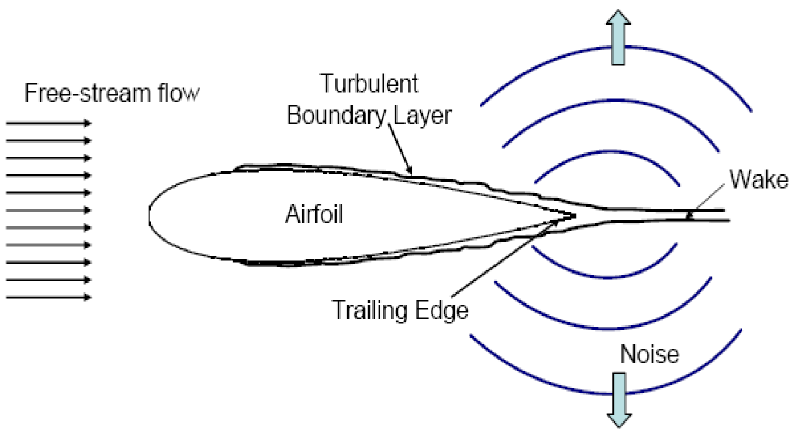

Fig. 12 – Noise generated by the airfoil

Main noise mechanism of a clean wing is the turbulent boundary layer-trailing edge (TBL-TE) noise. Trailing edge noise originates primarily due to the scattering of some of the energy in the eddies directly into acoustic waves during the passage of a turbulent boundary layer over the trailing edge of wings or flaps (Fig. 12). Turbulent pressure fluctuations in the wing boundary layer within an acoustic wavelength of the trailing edge are responsible for the noise generation. The spectrum of the trailing edge noise ranges from 100 Hz to over 10 kHz as shown in the experiments of Brooks [8].

Most of the theories used in predicting trailing edge noise are based on Lighthill's acoustic analogy. Lighthill modeled the problem of sound generation by turbulence in an exact analogy with sound radiated by a volume distribution of acoustic quadrupoles embedded in an ideal acoustic medium. In mathematical form, Lighthill's analogy is the inhomogeneous wave equation written for the acoustic density fluctuations ρ:

$$\frac{\partial^2 \rho}{\partial t^2} - a^2 \cdot \nabla^2 \rho = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j} \tag{1}$$

Here, a represents the speed of sound of the undisturbed fluid. The term T_{ij} is Lighthill's turbulence stress tensor and can be approximated as the unsteady component of the Reynolds stress in low Mach number flows. In Lighthill's analogy, the problem of calculating the aerodynamic sound is equivalent to solving Eq.1 for the radiation of sound into a stationary, ideal fluid produced by a distribution of quadrupole sources whose strength per unit volume is Lighthill's stress tensor T_{ij}.

Following the approach by Goldstein one can approximate the far-field noise intensity per unit volume of acoustic sources at the trailing edge of a wing as

$$I \approx \frac{\rho_\infty}{2\pi^3 a_\infty^2 H^2} \cdot \omega_0 \cdot u_0^4 \tag{2}$$

where ρ_∞ is the free-stream density, a_∞ is the free-stream speed of sound, ω_0 is the characteristic source frequency, u_0 is the characteristic velocity scale for turbulence, H is the distance to the ground (receiver).

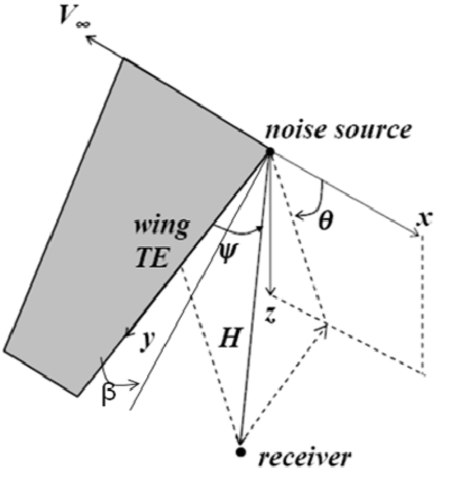

Fig. 13 – 3D geometry for trailing edge noise metric

This equation is a form of the Ffowcs Williams- Hall equation given by Goldstein. Eq. 2 gives the noise intensity at a point in the flyover plane where the polar angle is 90 deg, and it is written for a trailing edge sweep angle of zero. Therefore, it does not show the dependency of the noise intensity on the directivity and the trailing edge sweep angles. Trailing edge sweep angle dependency can be introduced in Eq.2 in a very direct way as:

$$I \approx \frac{\rho_\infty}{2\pi^3 a_\infty^2 H^2} \cdot \omega_0 \cdot u_0^4 \cdot \cos^3(\beta) \tag{3}$$

If we consider a more complex geometry as in Fig. 13, the noise intensity for any point in the far-field can be expressed including the directivity term $D(\theta,\psi)$ in Eq. 3 as follows:

$$I \approx \frac{\rho_\infty}{2\pi^3 a_\infty^2 H^2} \cdot \omega_0 \cdot u_0^4 \cdot \cos^3(\beta) \cdot \frac{D(\theta,\psi)}{H^2} \quad \text{where} \quad D(\theta,\psi) = 2 \cdot \sin\left(\frac{\theta}{2}\right) \cdot \sin(\psi) \tag{4}$$

Present analysis proposes a new noise metric and a global procedure that may be used for optimization problems involving aerodynamic noise from a clean wing. This metric is based on a classical trailing edge noise theory as the starting point where we include characteristic velocity and length scales that are obtained from three-dimensional URANS simulations with k - □ turbulence model. Proposed metric is based on the integral formulation of Eq. 4 as:

$$I = \frac{\rho_\infty}{2\pi^3 a_\infty^2} \int_0^b u_0^5 \cdot l_0 \cdot \cos^3(\beta) \cdot \frac{D(\theta,\psi)}{H^2} \cdot dy \tag{5}$$

and then the definition for the Noise Metric NM:

$$NM = 120 + 10 \cdot Log(I) \tag{6}$$

We compare this metric with existing Lockard and Lilley [9] formulation like:

$$I = K \cdot \frac{V_\infty M_\infty^2 W}{C_L H^2} \left(1 + \frac{1}{4} C_L^2\right)^4 \tag{7}$$

where there is no specification for the spanwise variation of the velocity and length scales, which tends to become important at high lift coefficients for three-dimensional cases.

In the new Noise Metric, the characteristic turbulent velocity at a spanwise location of the wing trailing edge can be chosen as the maximum value of the turbulent kinetic energy (TKE) profile at that particular spanwise station. If we take z_n as the direction normal to the wing surface, then:

$$u_0(y) = Max\left(\sqrt{TKE(z_n)}\right) \tag{8}$$

At the same time we proposed here that the characteristic turbulence length scale for each spanwise station can be represented by:

$$l_0(y) = \frac{Max\left(\sqrt{TKE(z_n)}\right)}{\omega} \tag{9}$$

where ω is the turbulence frequency (dissipation rate per unit kinetic energy) observed at the maximum *TKE* location. This choice of a length scale is directly related to the turbulent characteristics of the flow and is indicative of the size of the turbulent eddies that produce the noise. It can be viewed as more soundly based than other suggestions in the literature like the boundary layer thickness or the displacement thickness. Those lengths are related to the mean flow and reflect little about the turbulence structure.

The turbulent kinetic energy (TKE) and the turbulence frequency (ω) are obtained from the solutions of the k-eps. turbulence model equations used in the URANS (Unsteady Reynolds Averaged Navier-Stokes) calculations. This information for the F15 configuration will be available at the end of the post-processing phase of the experimental data, combined with the information presented in the previous chapter.

Global evaluation of the noise metric will be performed in the next phase of a complex project at EU level. Also, in JTI Clean Sky, INCAS will continue this work in SFWA ITD, also with proposed extensions in GRA ITD.

4. CONCLUSIONS

Following the test campaigns for 2D and 2.5D configurations, from the large amount of experimental data obtained, one may formulate some preliminary conclusions, as follows.

- AFC using oscillatory blowing in the flap gap is a promising technology, with potential to influence high lift systems especially in non-optimised configurations. This effect is stronger in 2D cases and decreases with sweep angle in 2.5D configurations.
- For optimised configurations, AFC is effective at higher mass flow rates, at frequencies from 100 to 150 Hz. Lift increase is significant, so this is an important aspect to take into account in future designs.
  From the experimental information, the AFC proposed was close to a maximum efficiency, as presented in Fig. 3. This is possible caused by the implementation of the system in the flap and with direct relation on the design of the actuators. New design parameters might extend the potential of this technology.
- There was no optimization of the settings of the high lift system (gap-overlap-deflexion) to include the presence of the AFC. Global optimization taking into account AFC might enable greater efficiency for the technology.
- With respect to current implementation in the laboratory environment, AFC using oscillatory blowing is a mature technology at TRL level 4 and might be considered for higher TRL development in JTI Clean Sky.
- Proposed noise metric might represent a possible evaluation criteria for the AFC as candidate to HiLON (High Lift Low Noise) concept.

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