WIND TUNNEL INVESTIGATION FOR OSCILLATORY BLOWING ON HIGH LIFT SYSTEMS

Catalin NAE*
***INCAS - National Institute for Aerospace Research**
Bucharest, ROMANIA

Keywords: *active flow control, high lift systems, wind tunnel testing*

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.

Initial experiments on 2D configuration were based on the work performed in AVERT EU FP6 project, where the oscillatory flap gap blowing system was designed and tested on a INCAS F15 2D wing model. 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 data was mainly oriented towards system efficiency and TRL evaluation for this active technology.

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.

2 Oscillatory Blowing System Architecture

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] (Figure 1).

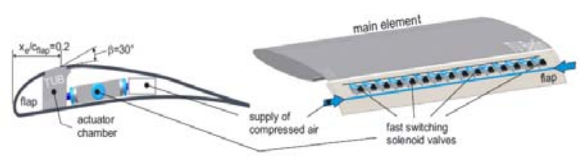

Fig. 1. AFC using oscillatory blowing

The system architecture to be implemented in the flap is presented in Figure 2. This design, proposed by TU Berlin and evaluated in several other testing campaigns [4] was selected for further investigation in AVERT project.

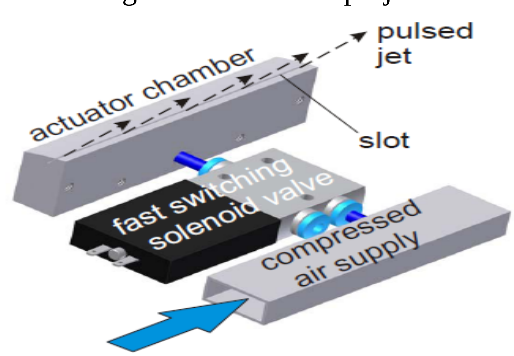

Fig. 2. AFC system architecture

The expected results include detailed measurements from a six- component wind tunnel balance and pressure sensors readings.

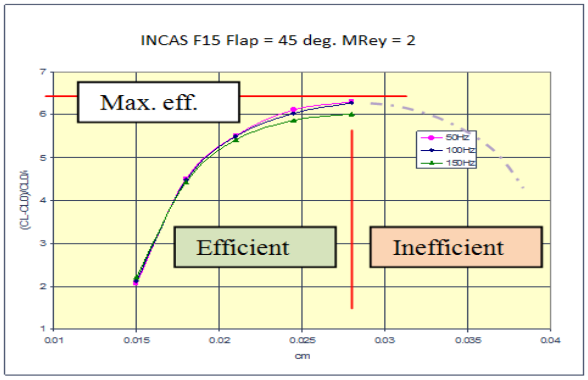

Fig. 3. AFC efficiency in 2D configurations

For the system under investigation, efficiency is considered based on the global effect of the oscillatory blowing system as presented in Figure 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.

3 The Model for AFC

A dedicated model (INCAS F15), based on F15 geometry has been designed and manufactured for wind tunnel testing at INCAS subsonic wind tunnel [5].

The maximum wind tunnel test room in the tunnel is 2.5m width & 2 m height; the maximum permissible span of the model is aprox. 2.0m, in order to make room for side edges and to enable popper distance to the side walls of the test section. In order to achieve a high Reynolds number in the range of 3 million (for wt speed close to 90 m/s), the basic chord length was selected as 600 mm. For reference, the global span of the model is 2.050 mm, with a minimum chord length of 600 mm (basic configuration – cruise). This gives a global aspect ratio of 2.0/0.6 = 3.333 for cruise configuration and lower for HL configurations.

3.1 Model Design

This model has movable flap capability with independent control for flap gap, overlap and rotation. The flap was designed so that 19 actuators could be integrated in a 2m span of the flap and tested in a wide range of blowing conditions for the proposed high lift configurations (Figure 5).

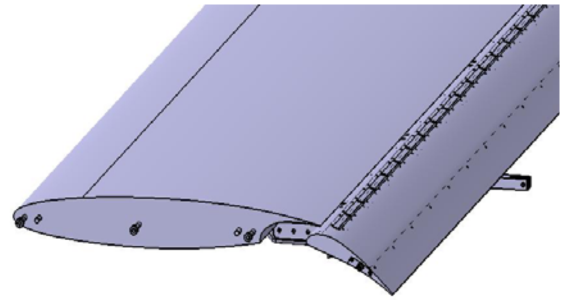

Fig. 5. INCAS F15 model for AFC

The actuators for oscillatory blowing are located in the movable flap, with a global geometry indicated in Figure 6. This setup is based on the work performed in AVERT project, where TU Berlin has designed and manufactured the actuator chamber as presented in Figure 7.

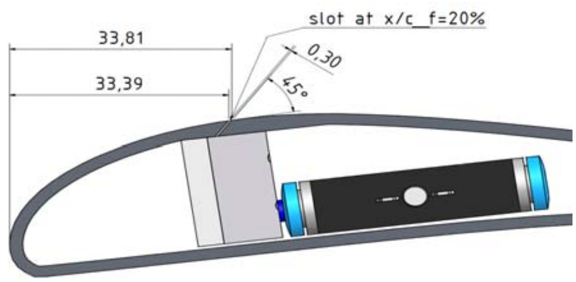

Fig. 6. Installation of the actuators in the flap

The actuator has a slot width of 0.3 mm, a slot length of 90 mm and the blowing angle is fixed at 45 deg. The inner part of the actuators chamber has a symmetric inner contour and generates a symmetric velocity profile for the jet at the slot exit. The actuators have been integrated in the model with dedicated system for pressurized air tailored for maximum 9 bar.

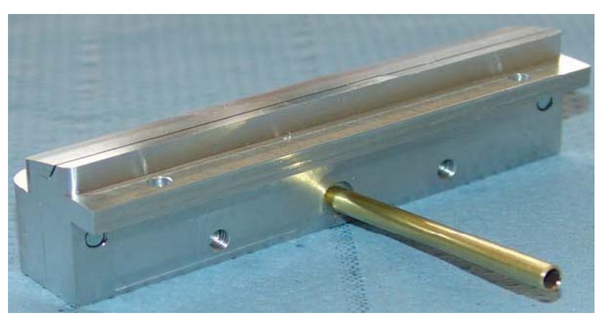

Fig. 7. Actuator's chamber

All 19 actuators are connected to a global pressure distribution system integrated inside the flap (Figure 8). The system was designed and tested so that all actuators could be operated in normal conditions for a pressure up to 9 bar, either together or individually, without mass flux limitations.

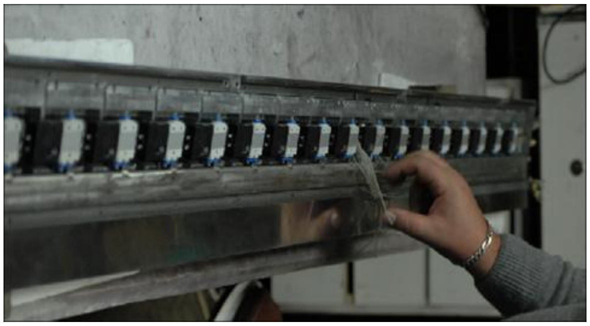

Fig. 8. Global instrumentation inside the flap

3.2 Model Instrumentation

The INCAS F15 wing and flap were instrumented for pressure coefficients measurements by means of 2x2x48 port model D scanivalves installed inside the wing model and 4x16 digital scanning system for the flap.

A total of 59 pressure orifices (1 mm dia., 34 orifices on the upper surface and 25 on the lower surface) were drilled on the wing model in each of the 3 sections. In a similar mode 28+29=57 pressure orifices were drilled on the flap model (15 on the upper surface and 14 on the lower surface, 28 in section 1 and 29 in section 2). The holes were positioned using specially built templates. In each section, the holes on the wing model were arranged along 2 lines parallel with respect to the flow direction in alternative sequence in order to minimise flow interference and preserve natural character of the boundary layer upstream of each hole.

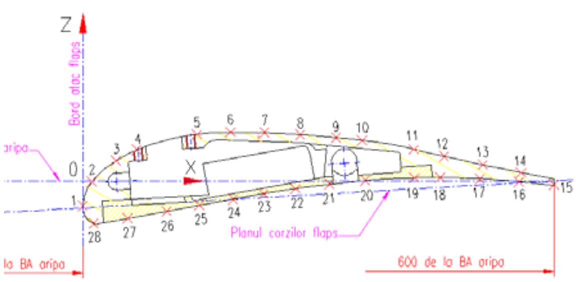

Fig. 9. Flap instrumentation Cp measurements

The holes on the flap were arranged along 2 chordwise lines downstream of the holes corresponding to the upper surface wing trailing edge. Short lengths of 1.5 mm O.D. brass tubing or 1 mm O.D. steel tubing were bonded to each hole to allow pneumatic connections to the scanivalves via 1.5 mm I.D. plastic tubing. The plastic tubes from the flap model were bundled together in a loop partly attached to the middle flap bracket and then passed inside the wing model to be connected to the scanivalves. The loop length allowed the flap to be positioned at all required positions with respect to the wing.

The two scanivalves were equipped with ±2.5 psid DRUCK differential transducers, ±0.25% accuracy, excited with 12 Volts by the existing system. Full scale signal was cca. 1.3 Volts for Scanivalve A and 1.5 Volts for Scanivalve B and these values were monitored during the tests in order to avoid overloading the transducers. The other 2 scanivalves used ±5 psid DRUCK differential transducers.

3.3 Model Validation

According to INCAS AQ procedures, the model has been analyzed and validated prior to the wind tunnel test campaign, based on the experimental program definition (test matrix). The structural model (Figure 10) was intended for analysis in both passive and active evaluation of the system, with a special attention for the case of oscillatory blowing with respect to the movable flap mechanism.

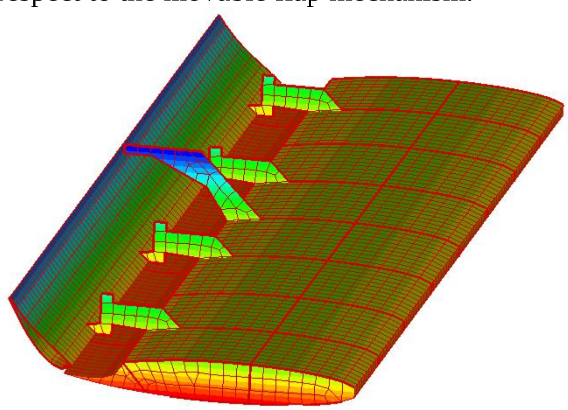

Fig. 10. INCAS F15 - structural analysis model

Specific results from this analysis for deformations and vibration of the model is given in Figure 11. This was correlated with a dedicated analysis including mounting system in the tunnel (external balance) and resonance frequency of the global setup.

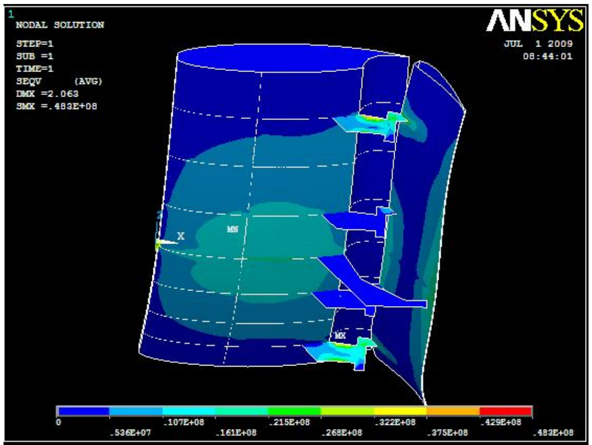

Fig. 11. INCAS F15 model - structural analysis

Following validation of the model, the system was installed in the wind tunnel for preliminary calibrations.

The active flow system was designed so that the following parameters could be reached and continuously monitored during the tests:

- Blowing pressure in the range of 2 – 8 bar, from 25Hz to 250 Hz
- Continuous pressure monitoring and stabilization in the blowing system
- Actuators could be operated individually and/or in arrays.
- Individual mass flow rate measurements and for global array

The validation for these characteristics was performed using a dedicated test bench as presented in Figure 12

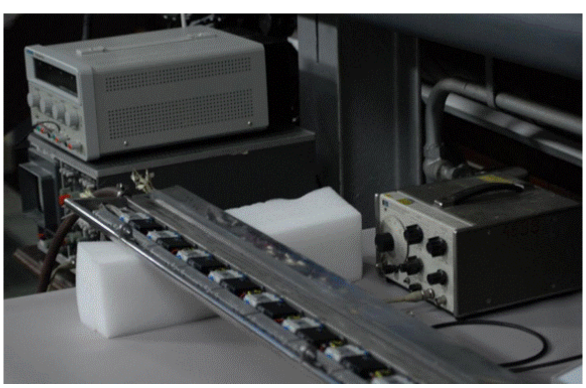

Fig. 12. Flap validation for AFC

Tests performed validated the initial design parameters for the oscillatory blowing system. Velocity measurements with hot wire anemometer indicated, at 8 bar, 100 Hz frequency and 50% duty cycle, average local speed of 35 m/s, with a peek up to 65 m/s, as presented in Figure 13.

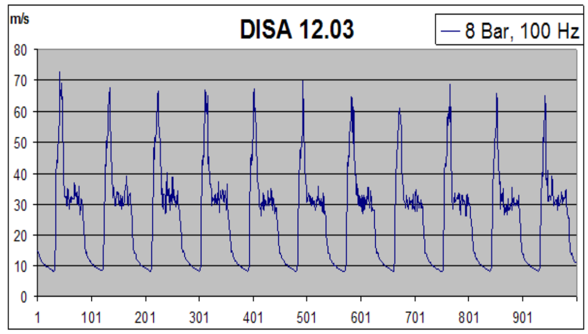

Fig. 13. Local velocity measurements for individual actuators

4 The Experimental Setup

Wind tunnel test have been conducted in INCAS Subsonic Wind Tunnel facility. This is an atmospheric, closed circuit wind tunnel, with maximum speed up to 110 m/s. The test section is 2.0mx2.5m, with an external balance of pyramidal type.

The global setup proposed for experiments was as for a 3 mats horizontal mounting of the model, with simultaneous data acquisition for global loads (with the external balance) and pressure data acquisition. Global layout is presented in Figure 14.

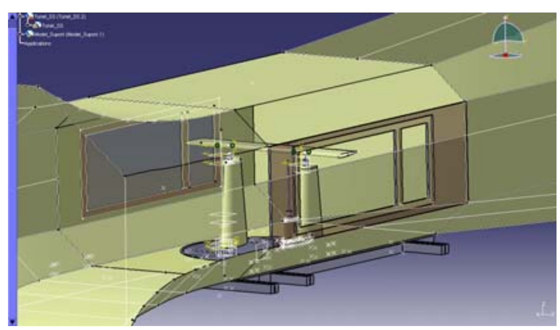

Fig. 14. Global experiment setup at INCAS

There were 2 campaigns for testing. The first campaign was dedicated to 2D investigation of the oscillatory blowing system, as part of AVERT project (Figure 15). The second campaign extended results to 2.5D evaluation of the system.

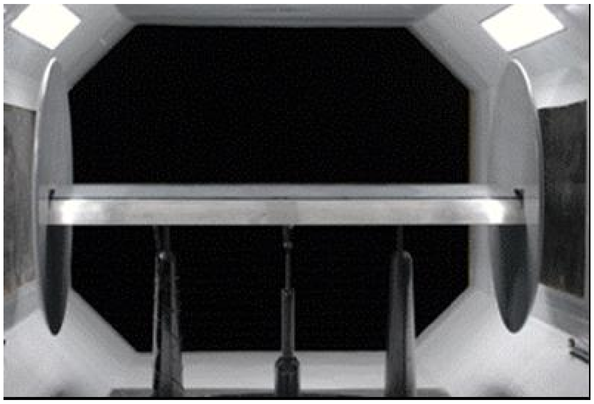

Fig. 15. INCAS F15 model in the wind tunnel

4.1 Experimental Program

The experiments in the Subsonic Wind Tunnel at INCAS have been conducted so that we could benefit from the medium size of the facility and to enable large model validation. The test matrix was defined in order to achieve several objectives, as follows:

- The air speed for tests was from 50 to 60 m/s for all tests. The speed is correlated with the Reynolds number (aprox. 2.0 ... 2.5 million)
- Global loads under maximum balance capacity (AoA limited so that maximum Lift is under 10.000 N)
- Reynolds similitude evaluation in the range of 2 to 2.5 million – Global Loads and main aerodynamic coefficients
- Basic experiments considered for Reynolds number close to 2 million for comparison with existing data and previous experiments.
- Pressure distribution, global loads and main aerodynamic coefficients evaluation for 2D and 2.5D configurations;
- Pressure distribution for specific Reynolds number (2 million) in incidence range -10 to +15 deg.

4.2 Model Installation

There were two main problems related to the installation of the model inside the wind tunnel. The first was related to a possible interference with the natural frequency of the mounting system in the range of about 250Hz. A dedicated procedure was used in order to evaluate natural frequency of the mounting system using the external balance. The result of this test was that the system enables frequencies up to 300 Hz without potential resonance problems.

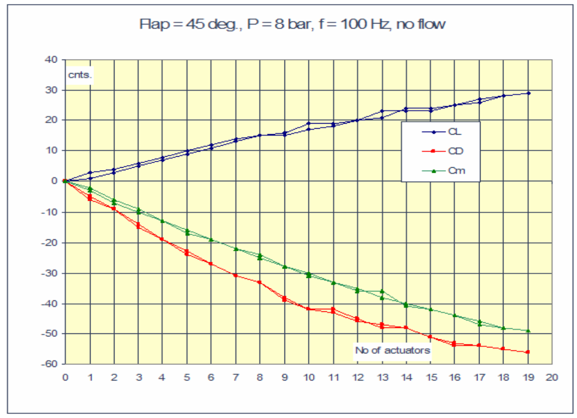

Fig. 16. Balance response to AFC - test w/o flow

The second problem was related to the possibility of the external system to capture the effect of the oscillatory blowing. In order to test this capability, a special testing procedure was used, without flow, where the actuators were started one by one up to 19, followed by a recovery sequence of turning them off. The response of the external balance was recorded for global loads, as presented in Figure 16. Since incremental response was recorded and limited hysteresis followed, it was concluded that the system is accurate enough to enable global loads for the model in the oscillatory blowing regime.

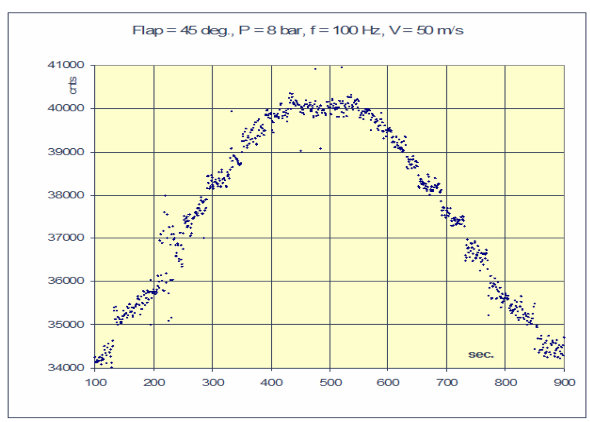

Fig. 17. Balance response to AFC - test with flow

A similar procedure with flow was used in a second phase, also turning on/off the actuators incrementally. The procedure was used with a 10 seconds step in order to enable full stabilization of loads, as recorded by the external balance. The system response is presented in Figure 17.

4.3 Test Matrix

The experimental program considered was divided in two separated test campaigns. The first campaign was intended for 2D evaluation of the AFC, using three settings for the flap (40, 45 and 49 deg.) three mass flow rates as enabled by the auxiliary pressure system (4, 6 and 8 bar, see Figure 18) and actuator frequency from 25 up to 200 Hz. The second campaign was dedicated to the evaluation of the AFC in 2.5D configuration, with sweep angles of 20 and 25 deg., for the same parameters as in 2D test cases for the actuation system

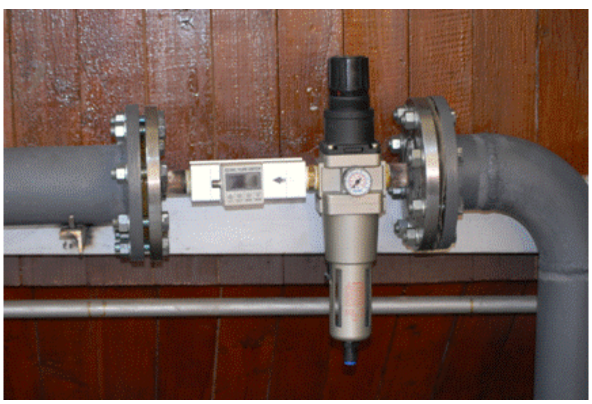

Fig. 18. Mass flow rate measurement system

All tests have been conducted to an equivalent Reynolds number of 2 million, and for a incidence range from -10 to +15 deg. The maximum incidence was limited by the total normal load enabled by the mounting system.
All tests have been performed with simultaneously recording of pressure data with scanning system and external loads with the balance. The basic configuration was considered at zero AoA (uncorrected value) and pressure distributions were recorded and selected as reference values for the basic flow on the model without flow control (Figure 19).

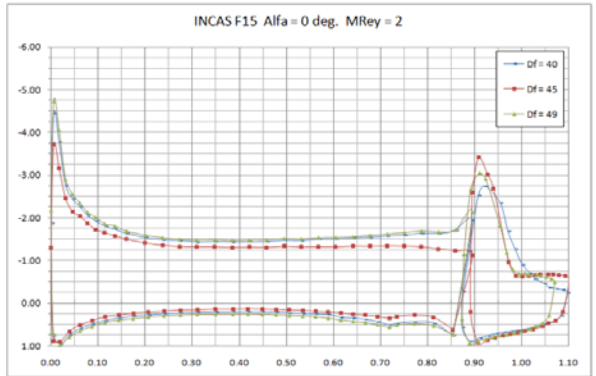

Fig. 19. Basic flow configuration - 2D cases

At the same time, from both readings of the external balance and also from pressure integration, reference values for the global lift of the 2D configuration was recorded (Figure 20). These values have also been investigated with respect to Reynolds number influence (from 1 to 3 million), repeatability and global errors of the data acquisition system.

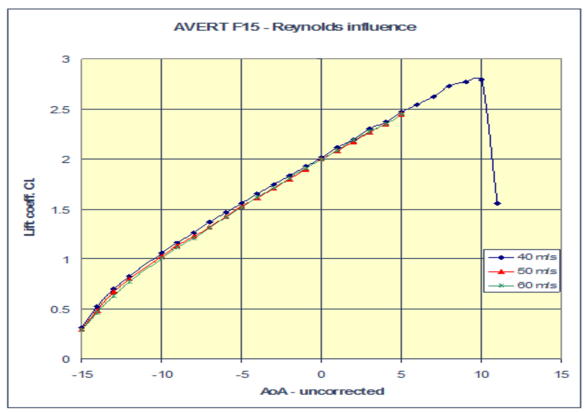

Fig. 19. Reynolds influence on the experiments

At the same time AFC was investigated using laser visualization system in order to enable full characterization of the oscillatory blowing technology.

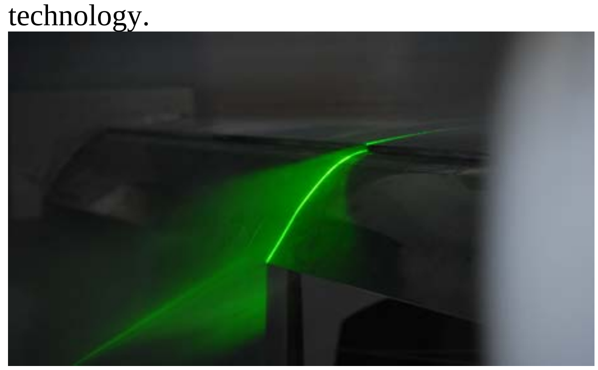

Fig. 20. Laser visualization - Flap 45, no AFC

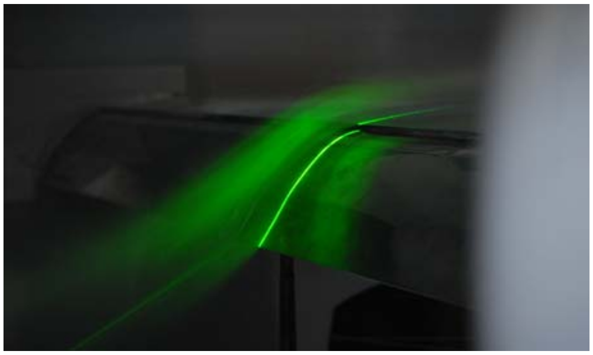

Fig. 21. Laser visualization - Flap 45, with AFC

Specific smoke-laser and luminescent oil paint were used for various regimes, as presented in Figure 20 and 21.

5 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.

5.1 Results for 2D Configurations

Tests were performed in order to identify potential benefit of the AFC on high lift system. From the pressure distribution in Fig. 19, 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.).

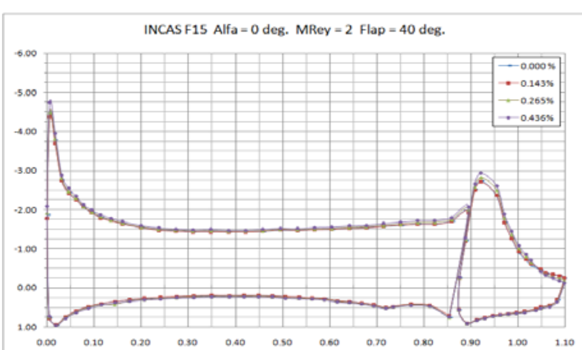

Fig. 22. AFC, Flap 40, AoA = 0 deg.

They have different response to the AFC (Figure 22, 23 and 24), with relative limited influence in the operating conditions (pressure from 4 to 8 bar and frequency from 25 to 200 Hz).

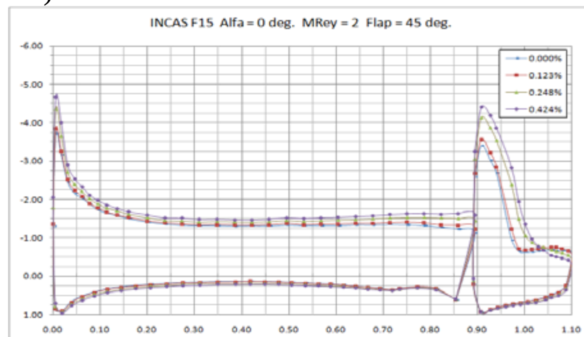

Fig. 23. AFC, Flap 45, AoA = 0 deg.

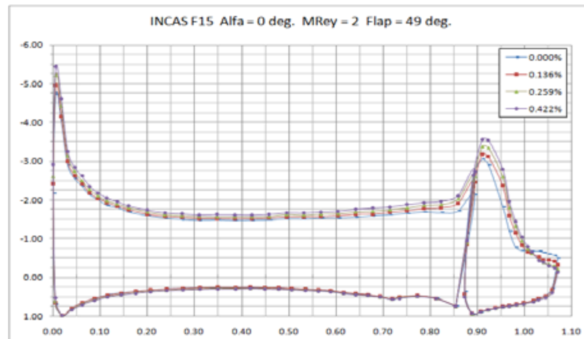

Fig. 24. AFC, Flap 49, AoA = 0 deg.

For example, the configuration with flap at 45 deg has also been investigated in a 2D CFD analysis, where large separation is observed, as in Figure 25. This flow pattern has also been investigated in the test campaign with oil paint, as presented in Figure 26

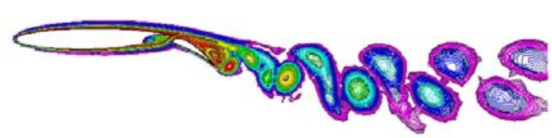

Fig. 25. CFD analysis, Flap 45, AoA = 0 deg.

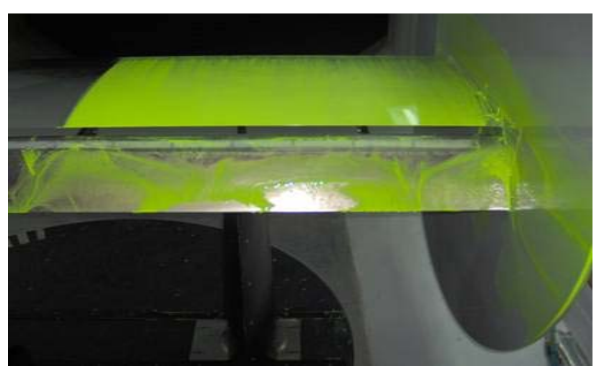

Fig. 26. Oil visualization, Flap 45, AoA= 0 deg.

This influence, for the 2D cases has been identified for all tests in the test matrix. As a consequence, tests have been orientated towards evaluation of oscillatory blowing system parameters with respect to both optimized and un-optimized configurations, where different interaction mechanisms are presented.

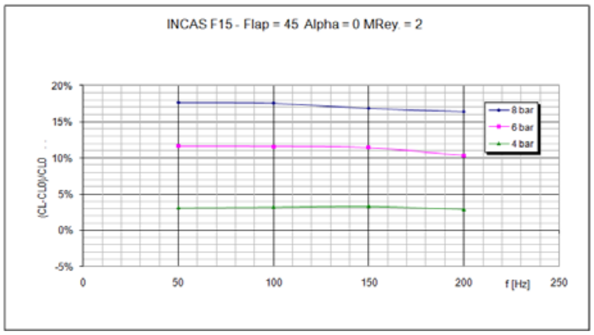

Fig. 27.Pressure-Frequency influence, Flap 45

As presented in Figure 27, the AFC has a potential to increase lift at frequencies from 100 to 150 Hz, with an important effect at higher pressure, that corresponds to higher mass flow rates in the auxiliary system. This effect is valid for a global range of incidences, mainly for un-optimized flap settings, as presented in Figure 28. In these cases the basic mechanism is directly linked to the attachment of the flow due to the oscillatory injection of fluid.

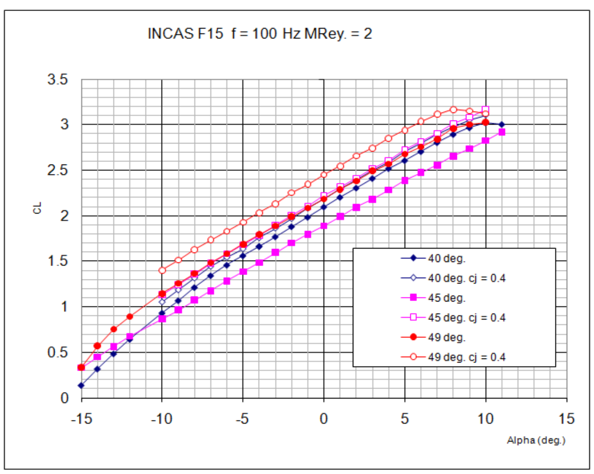

Fig. 28. AFC for 3 flap settings

At the same time, for the configuration with 49 flap deflexion, that has a rather optimized flow pattern without AFC, the tests showed lift increase with the increasing of the mass flow rate, and where attachment of the flow is present from the beginning (Figure 29).

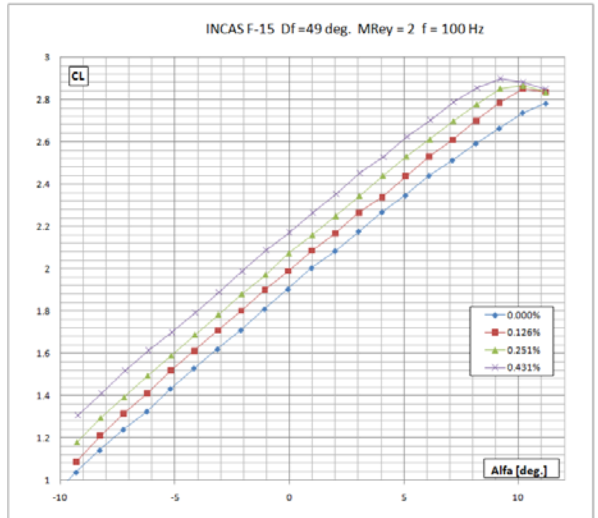

Fig. 29. AFC for different mass flow rates - Flap 49 deg.

As a global result from the test campaign on 2D configuration, system efficiency has been represented in Figure 30, where we have a dependency of the ration of relative lift increase to the mass flow rate as a function of the mass flow rate, for three frequencies, where significant lift improvement has been observed.

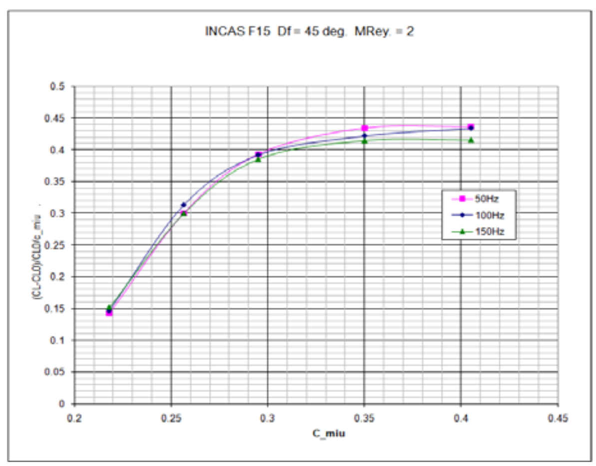

Fig. 30. AFC efficiency in 2D, Flap 45 deg.

5.2 Results for 2.5D Configurations

Tests for 2.5D configurations were performed using a limited number of changes to the wind tunnel model (with respect to end plates and pneumatic power supply), preserving all reference setups as compared with the 2D tests.

Sweep angles considered were 20 and 25 deg. Also, from oil visualization, inner section (having requested pressure taps) of the model was validated for 2.5D flow analysis.

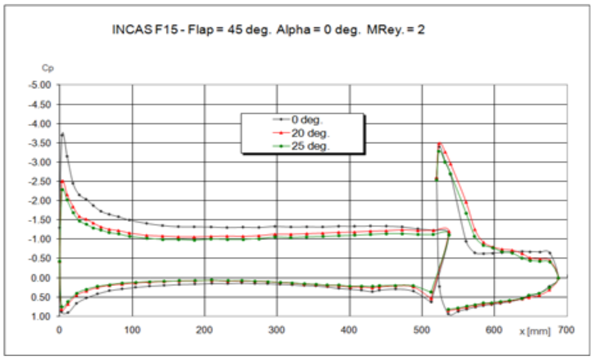

Fig. 31. Basic flow configuration - 2D cases

From pressure distribution, the basic flow pattern for the high lift system compared to the 2D case shows a lower detachment region on the flap, for all flap settings (Figure 31).

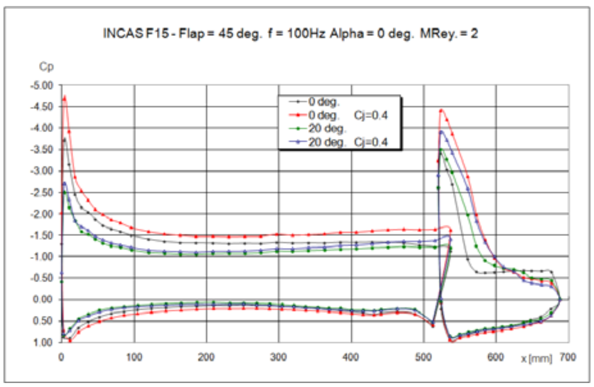

Fig. 32. AFC for Flap 45 deg.- 2.5D cases

From tests results, the influence of the AFC is still present in 2.5D cases, however with lower lift increase. This is mainly due to the fact that in 2.5D cases the flow is more attached to the flap surfaces, as presented in pressure distributions in Figure 32. This is consistent with the experiments for 2D cases.

Also, from global results, AFC is acting towards lift improvement, mainly for the 45 flap deflexion. This is also consistent with experiments in 2D case (Figure 33). The system is still more active in flows with stronger separation areas, as for 45 flap deflexions, with lower influence on optimized configurations, as for 40 or 49 deg. flap deflexions.

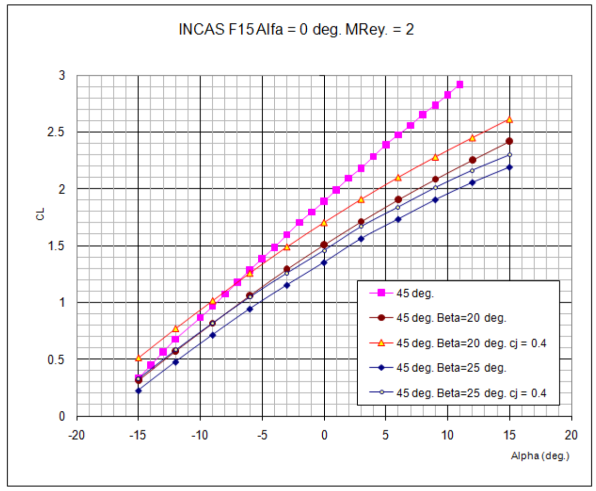

Fig. 33. AFC in 2.5D configurations

The effect of the sweep angle is to lower the AFC system efficiency, as a result of the more attached flow configuration associated with the 2.5D flow configuration. However, this was investigated for sweep angles up to 25 deg and this needs more investigation in order to formulate a clear statement.

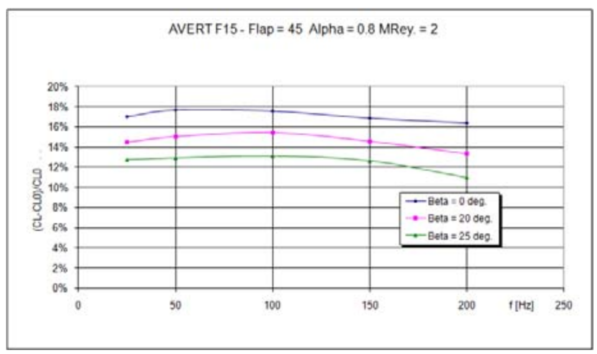

Fig. 33. Sweep angle influence on AFC efficiency - 2.5D cases

6 Some 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 Figure 3 and 30. 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 oscillatory blowing technology on the flaps.
- 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.

Acknowledgement

This work has been initiated in AVERT EU FP6 project and will continue in EU JTI Clean Sky, Smart Fixed Wing ITD.

References

[1] Nae C, *Flap gap oscillatory blowing on wings*, in INCAS Bulletin 2/2009, ISSN 2066- 8201

[2] Greenblatt D, Wygnanski I, *Use of periodic excitation to enhance airfoil performance at low Reynolds numbers*, Journal of Aircraft, Vol. 38, No.1:pp. 190–192, 2001.

[3] Haucke F, Peltzer I, Nitsche W, *Active separation control on a slatless 2D high lift wing section*, ICAS 2008

[4] Wild J, Haucke F, Scholz P, *Large scale separation flow control experiments within the German Flow Control Network*, KATNet II Separation Control Workshop, 1-3 April 2008, Toulouse

[5] Nae C, Pricop V, *Wind Tunnel Test Report*, EU FP6 AVERT Project, D2.1.4/D2.1.5 - Jun 2009

Contact Author Email Address

dr. Catalin NAE, cnae@incas.ro

Copyright Statement