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APPLICATION OF ACTIVE FLOW CONTROL ON AIRCRAFTS - STATE OF THE ART

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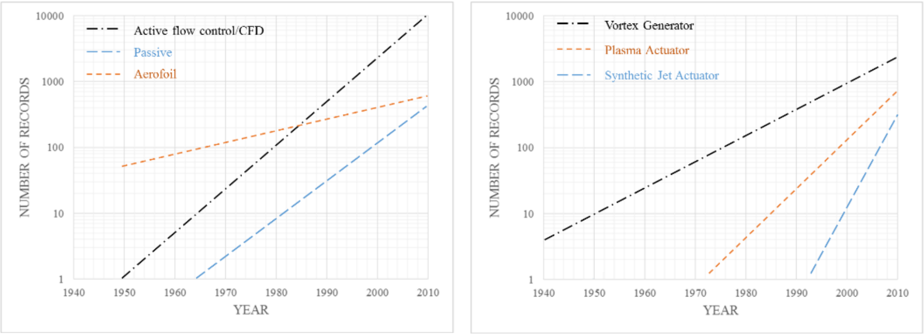
Abstract

This paper reviews and highlights the current state of the art on active flow control applied to civil aircrafts. A brief introduction presents the flow control research field and the technology readiness levels already reached to answer civil aircrafts needs. Then different types of flows around an aircraft are discussed as a potential applications of flow control. A short review of active flow control actuators is made with a focus on those more adaptable to be applied on civil aircrafts. Finally, the main difficulties to overcome in order to reach technology readiness levels allowing application on civil aircrafts are mentioned.

1 INTRODUCTION

Flow control (FC) strategies are generally employed to delay/advance transition, to enhance/eliminate turbulence and/or to prevent/induce separation in order to increase the lift, decrease the drag, increase the mixing or suppress the flow-induced noise [1]. In aeronautics, the ultimate goal is to reduce the environmental footprint by reducing fuel consumption by enhancing aircraft aerodynamics. Even though many passive FC techniques (riblets, fences, vortex generators, etc.) have been successfully applied on aircrafts, active FC ones drew researchers attention for their ability to be activated only when and where they are needed. Thus, a huge amount of studies have been conducted during the last two decades, during which researchers tested many types and concepts of actuators. While results obtained numerically by CFD and experimentally in wind tunnel are promising, they need to be relevant, as noted in a relatively recent paper [2]. According to this later, on a few of the recently published research works in the field of flow control dealt with ‘flight test’ or ‘integration’ of Active Flow Control (AFC) technologies. These studies stay thus far away from any maturity allowing them to be adopted by aircraft industry (Figure 1). On the other hand, most of these researches had focused on the idea of replacing existing technical solutions (high lift devices for example) by Flow Control Systems (FCSs), which is still too difficult to achieve considering the present maturity level of the FC research field [3], ignoring industrial feasibility, cost effectiveness and certification issues. In the following sections, we will highlight the industrial needs and research done until now to satisfy these needs.



(a) (b)

Figure 1 – Historical growth of engineering research areas based on the number of records per year in the Compendex engineering database (1949-2007) according to [2]
(a) specific aerospace related research areas, (b) flow control actuator technologies

2 WHERE ACTIVE FLOW CONTROL CAN BE APPLIED ON CIVIL AIRCRAFTS?

Generally speaking, AFC is mainly employed to overcome flow separation (caused by high adverse pressure gradients) on smooth surfaces, on after-bodies and on two surfaces junctions [4]. On a civil aircraft, it could help to increase the effectiveness of high lift systems and control surfaces, to reduce the noise due to undercarriage, and finally, to modify locally the flow in some areas (e.g. flap slide edges, wing-pylon junctions) [3].

As aircraft wings are the main generator of lift on aircrafts, but also a main source of induced drag, designers have to optimize wings design and, of course, the whole other parts serving the principal mission of the airplane. A civil aircraft is optimized for cruising flight, and equipped with high-lift devices (HLD) (leading edge slats and trailing edge flaps) to soften the impact of high angle of attack during take-off and landing phases. These mechanical devices allow, via a geometrical modification of the wing, a favourable modification of the pressure distribution and to re-energize the boundary layer, thus obtaining more lift for higher critical angles of attack. But modern civil aircraft wings equipped with HLD are still vulnerable to airflow separation in three critical zones: the wing root, the wing-pylon junction and the wingtip.

More engines with high/ultra-high-bypass are used nowadays on civil aircraft. To keep a reasonable clearance with ground, the engine nacelle must be closer to the wing, and consequently, leading edge slats suffer a cut-out to avoid collision with the nacelle during their deployment for take-off or landing. It was found [5] that air flow around the wing-pylon junction is dominated by seven different types of vorticities as shown on Figure 2. Similarly, longitudinal vortices are generated at wing root (inboard side of slats) because of the slat less leading edge portion [6]. On the other hand, the curved wing tips (called sharklets) are designed and optimized to reduce wing tip vortices and thus lift-induced drag, and to contribute in lift generation during cruise phase. So, at high angles of attack, airflow may separate decreasing lift [7].

Active flow control techniques could be employed not only to overcome these undesirable phenomena, but also to enhance the performance of other parts of aircrafts such like the vertical tail surface. The latter has a vital mission not only for the stability of the aircraft during several normal phases of flight but also for the case of loss of an engine during flight, where it must generate a side force to keep a directional stability with asymmetric thrust and overcome the drag generated by the lost engine. However, this part has the same size for all aircraft versions belonging to the same family where it is sized for the smallest one; as a result, it is oversized for the longer versions and represents an unnecessary load and drag.

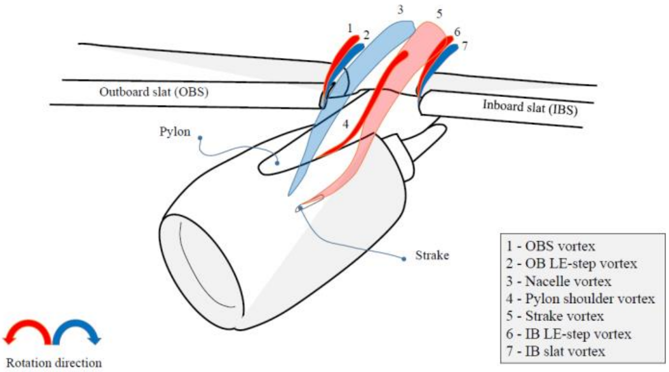


Figure 2 – Flow topology around wing-pylon junction (*according to* [5])

Employing AFC technology could be useful to delay flow separation for high deflection angles of the rudder in case of engine-out or high crosswind. Enhancing the performance of the vertical tail will open the possibility to resize it. Authors of [8]–[11] tested an AFC system based on sweeping jet on a full-size Boeing 757 vertical tail. Using a series of 31 actuators, the side force was increased of more than 20% for the maximum rudder deflection (30°) at 100 knots in a wind tunnel (Figure 3), and estimated to be in the range (13%-16%) for inflight test for the same conditions. They estimate that the induced reduction in fuel consumption can achieve 15,500 gallons/airplane/year.

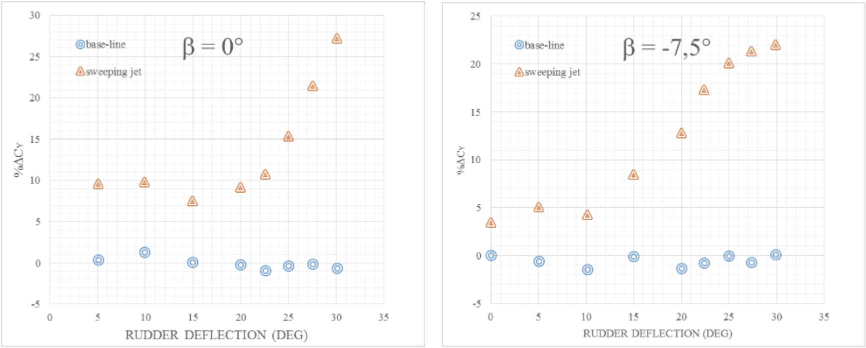


Figure 3 – – Vertical tail side force enhancement using sweeping jet (*according to* [9])
(U_∞ = 100 knots, β=side slip angle, $\%\Delta C_y$ = difference in side force coefficient)

3 ACTIVE FLOW CONTROL ACTUATORS

As cited in many papers such as [6], [12], the flow control field dates back to early experiments on boundary layer conducted by Prandtl. Generally, flow control methods can be classified in two categories: Active, which requires an external source of energy to feed actuators, and passive, which involves a geometrical modification and do not require any external source of energy [13]. In an AFCS, the actuator is an essential element and the characterization of its behavior and its effect on the controlled flow is required to establish effective control laws. AFC actuators can be classified according to many criteria, such as input energy (mechanical, fluidic, acoustic or thermal) [14], topology: orientation relative to external flow (tangential or lateral) [14], function [12] (Figure 4). In addition, an actuator can also be characterized by its frequency response (variation of magnitude and phase of the output versus actuation frequency) and bandwidth (range of actuation frequencies for which the output is large enough) [12]. The choice of a suitable type for a given application depends on its capability to reach the control goals with the least energy consumption.

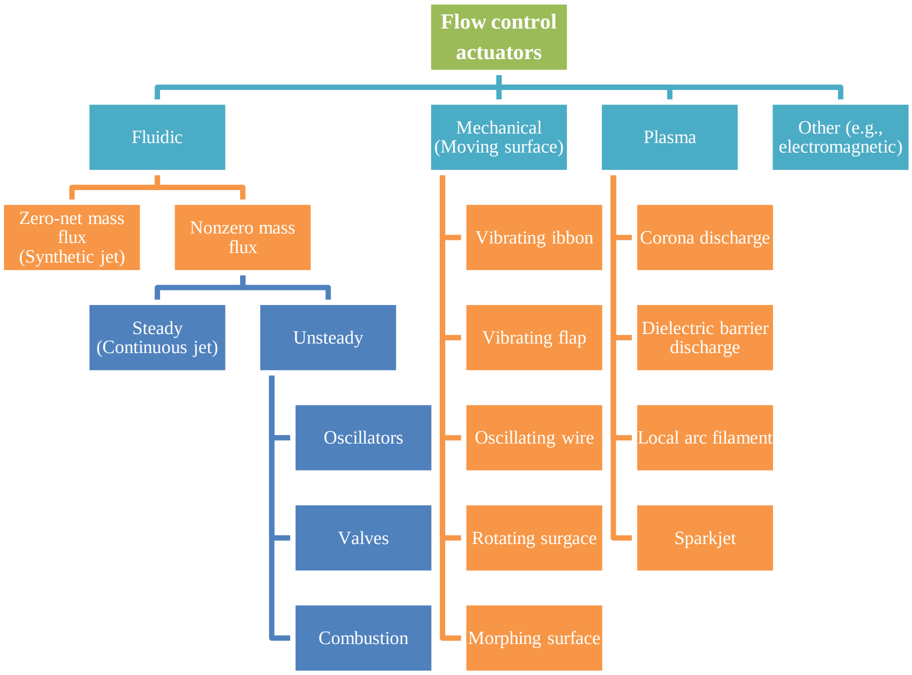


Figure 4 – Classification of flow control actuators based on function (*according to* [12])

Most of these actuators have been well studied and characterized in research laboratory conditions at low speed (low Reynolds number), but their Technology Readiness Level (TRL) is not yet high enough to allow an application on civil aircraft, mainly due to industrial issues related to robustness, cost effectiveness, reliability and certification and finally integration [2] [3] [6].

In order to compare the efficiency of different type of actuators for a given configuration, each device can be defined by three normalized parameters. These are [6]:

- **the momentum coefficient C_μ** (Actuation amplitude) defined as the ratio of the momentum flux introduced by the actuator (J) to the momentum flux of the main airflow, which is the product of the main airflow dynamic pressure ($½\rho U^2_\infty$; U_∞ is the main airflow velocity), and a reference area (A_{ref}), hence written as [$C\mu = J/½\rho U^2_\infty . A_{ref}$]. Actuation with low Cµ allows controlling boundary layer separation, but a high Cµ allows controlling circulation. The critical value separating these two types of control varies between 2% and 5% depending on the configuration [15].
- **the Velocity Ratio VR** (Actuation velocity) defined as the ratio of the actuator output velocity (u_{jet}) to a reference velocity (local velocity or main airflow velocity) (u_{ref}), hence written as [$VR= u_{jet}/ u_{ref}$]. It is also called authority level and must be ≥ 1 to be considered high enough for flow separation control applications, unless it will be considered as low authority and could be efficient for transition control and skin friction drag reduction [16].
- **the dimensionless Frequency F^+** (Actuation frequency) defined as the product of the actuation frequency (f_{AFC}) and a reference length scale (l_{ref}) divided by a reference velocity (e.g. u_{ref}), hence written as [$F^+= f_{AFC} .\ l_{ref}/u_{ref}$]. It is reported that the recommended value of F^+ allowing reattachment is approximately in the range 1 to 1.3, and between 3 and 4 to prevent separation [6].

3.1 Mechanical actuators

Including moving surfaces, e.g. piezo-electric flaps, shape memory alloys, electroactive polymers [17], mechanical actuators present the advantage of a higher force to weigh ratio but their performances are limited by a low frequency and a high power consumption. Another functional disadvantage of these actuators is the moving part in contact with external flow, which leads to difficulties concerning maintenance and robustness when used on aircrafts.

3.2 Plasma actuators

Having many advantages including low mass, fast response time, no moving part and easy to install [12], these actuators could be used in low and high speed flows. Their main disadvantage is the high voltage (kV) they need which imposes potential issues related to electromagnetic interferences, noise level and heating.

3.3 Fluidic actuators

Actuators based on fluid flow are most suitable for low speed airflow control (turbulent skin friction drag reduction) [16] [18]. Fluidic actuators are the most common type [12], and have been studied widely during last three decades. They have the advantage of having no moving parts in direct contact with the external flow. By adding high-momentum fluid (by blowing) into the external flow or removing the low-momentum fluid (by suction) from it, they could be efficiently employed in airflow separation applications. The zero-net-mass flux (ZNMF) type, also called synthetic jet actuator (SJA), does not require any fluidic source. It consists in a closed cavity with an orifice/slot on one side and a moving wall/membrane (electrically, mechanically or electromechanically excited) on the other one. On the other hand, non ZNMF actuators require an external fluid source that can be steady (e.g. continuous jet) or unsteady (e.g., pulsed jet). Depending on their technology, the input energy can be electrical, fluidic, mechanical, electro-mechanical or electro-fluidic. Recent studies were conducted to evidence the efficiency, identify the system architecture and power requirements and deal with the integration issues of many types of fluidic actuators on real-size civil aircraft parts, in wind tunnel [5] [8] [10] [2], [16], [19], and inflight [8] conditions. In addition to the fluidic actuators mentioned previously, two promising innovative devices based on existing concepts have been explored for AFC on civil aircrafts: the sweeping jet actuator (SWJA) [15] and the two-stages fluidic actuator [20]. We will highlight these actuators in the two following sections.

3.4 Sweeping Jet Actuator

Firstly invented in the middle of last century, the main advantages of this type of actuator, shown in Figure 5, are that it only needs a steady supply of compressed air, it have no moving parts, and that it can re-energize, thanks to sweeping output, a wide area of the boundary layer [8]. In addition, even with a low level of Cμ, it has been able to remove airflow separation on an NACA0021 airfoil [15]. With an increased Cμ, it even causes a general augmentation of the lift over drag ratio. The flow control efficiency of this type of actuator was tested on a sub-scale and full-scale vertical tail of a civil aircraft in wind tunnel tests [9], [11] and inflight tests [8] respectively.

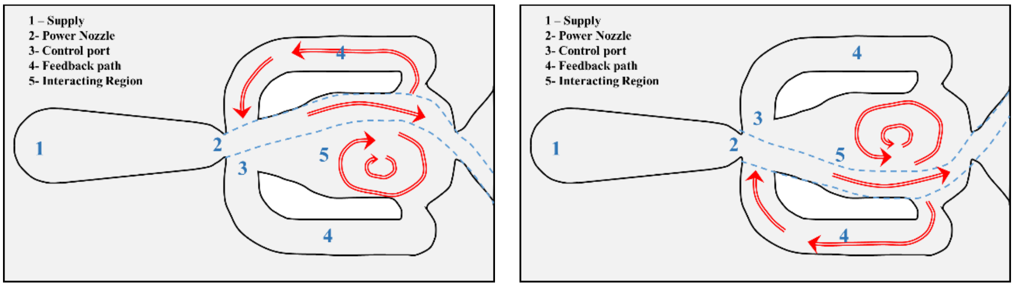


Figure 5 - Working principle of a sweeping jet actuator and visualization of internal flow (*according to* [15])

3.5 Two-stages Fluidic Actuator

Based on a combination of two different types of fluidic actuators, the two-stages fluidic actuator consists in a first oscillator named “driver stage” connected to an array of five diverters that form the second stage (Figure 6). Both stages are supplied by compressed air in such a way that the first stage produces a control mass flow which pilot the second stage diverters via five control port pairs. Two pulsed jets can be obtained from each diverter with 2π phased outputs. Using two stages allows a simple design as only the first stage oscillator needs feedback loops. Using different input pressure for each stage gives flexibility to control actuation amplitude and frequency independently. Studies in wind tunnel were conducted on a realistic outer wing model [7], [20] at take-off speed and showed that both stall angle and lift could be increased and that drag could be decreased using actuation. AFC might even be more efficient when the actuator outlets are largely spaced.

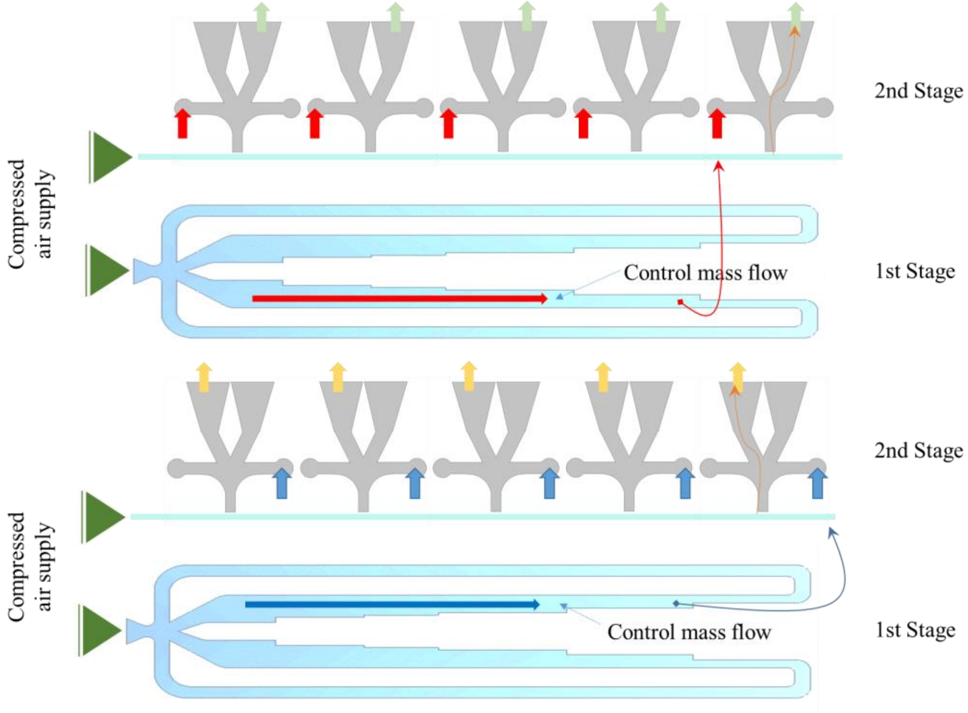


Figure 6 – Two-stages fluidic actuator system architecture (*according to* [20])

4 DIFFICULTIES TO OVERCOME

4.1 Filling the gap between academic research and actual applications

Even if a huge numbers of studies were related to flow control during the last 50 years (Figure 1), more than 75% of these studies focused on flow control fundamentals, technological developments or numerical tools for modelling but still from an academic viewpoint and quite far from what aircraft manufacturing really needs. Crowther and co-authors discussed this issue in a recent paper [2] and pointed out the main weaknesses making lot of research works on AFC irrelevant with regards to possible application on aircrafts (e.g. lack of deep knowledge in AFC aerodynamics, test of unrealistic configurations or focusing on one side of the real phenomenon and ignoring other important sides). To summarize, even if fundamental research in this field is still useful, the developed technologies should be tested, as far as possible, in industrially environments to get closer to the real application configurations.

4.2 Integration and power supply

Taking into account that high lift systems contribute to 6%-11% of an aircraft cost and add many tonnes to its mass, they could be the most suitable candidate to take advantage of FC technology [3] in low flight speed during take-off and landing for example. The geometrical properties of the part that could take advantage of FC technology and the availability of energy have an important impact on the AFC system architecture, mass and the choice of its components. The more efficiency required by the AFC system, the more the mass of this system is important [16] (1kg/kW for all electric AFC based on SJA without redundancy [3]).

One study conducted on a full-size Airbus A320 wing using pulsed jet actuators [19] showed that the choice of input energy (electrical or pneumatic) depends on the required amount of AFC output power. Full electrically powered actuators are more effective in mass for a power transmission lower than 20kW, and pneumatically ones are more competitive in mass for a power transmission higher than 20kW and up to 60kW. A hybrid powering system (electro-pneumatic) is recommended for more power transmission. According to the total power consumption and considering safety requirements, the power could be supplied by the main aircraft power system or by an individual source.

4.3 Reliability and certification

According to Figure 1, only a small part of AFC research have dealt with flow control systems integration and certification, and inflight performances. After half a century of research and development on the AFC concepts, the applicability of these systems and their conformity with civil aircraft regulations must now be tested. As any new technology, the AFC systems have to make proof in many fields, such as cost effectiveness, noise generated and reliability, to be fully applicable on civil aircraft, [3].

Considering the current TRL of the research works in this field, researchers expect a very late entry of AFC technology on civil aircraft. It could thus be more beneficial to implement these control systems on new aircrafts which could be designed taking them in consideration thus ensuring high compatibility and integration with aircraft systems, than to adapt existing civil aircrafts in order to integrate AFC systems.

As redundancy is a key feature of flight safety, the same safety measures must certainly be applied to AFC systems. This will increase both, the mass to power ratio of AFC systems and the ratio of the mass of the whole system with AFC to the mass of the original system without AFC.

5 CONCLUSION

Active flow control was regarded as the revolution that aerodynamics was waiting for, for a long time. One of the most important fields of applications of AFC, civil aircrafts, has been explored in this paper. Reviewing studies that have dealt with AFC techniques on civil aircrafts can be summarised by the following points:

- Despite the high number of researches conducted during more than fifty years, only a small portion has treated in depth the application of AFC on full-size civil aircrafts.

- AFC could be applied to enhance wing and control surface performance, to reduce noise and modify locally airflow in some critical areas on aircraft such as wing-pylon junction.

- Researches confirmed the efficiency of fluidic actuators to control flow separation on civil aircrafts. Actuators input energy type depends on the amount of energy to be transmitted to the controlled airflow (electric then fluidic and finally electro-fluidic).

- There are still many difficulties to overcome in order to achieve an operating AFC system on a civil aircraft, such as conducting research using realistic parameters and taking into account integration and certification issues for the final product.

To conclude, even if many active flow control concepts have proved to be efficient in laboratory environments, the technology readiness level of most of the research works conducted up to now is not yet high enough to envisage an integration on civil aircrafts in the near future. However, the next steps which will make a bridge between academic research and industrial applications are now well identified.

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