Active Boundary Layer Control

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1 Introduction

Active boundary layer control is a method of keeping the boundary layer on an aerodynamic flow attached or to delay the transition to turbulent flow. This can be applied once the separation is detected or before turbulent transition, to keep the flow attached for an extended period of time.

1.1 Boundary layer flow

When a fluid flows past any object, their interaction causes the flow to slow down as it approximates the surface, until, when in contact with the surface, the fluid's velocity is considered to be zero. The region in which the fluid's velocity varies from zero to the freestream velocity is called the boundary layer.

Within a boundary layer, as a flow travels around a surface, it is subjected to multiple disturbances, which may be amplified and cause a laminar flow to become turbulent [1]. This transition is one of the most critical aspects for aerodynamics, and although dependent on many parameters, transition flows often contain the following steps, according to Bertin [1]:

1. Stable/laminar flow; **2.** Unstable flow, with *Tollmien-Schlichting* (TS) waves; **3.** Development of 3D unstable waves and hairpin eddies; **4.** Region of high shear caused by vortex breakdown; **5.** 3D fluctuating flow, due to cascading vortex breakdown; **6.** Region of turbulent spots; **7.** Fully turbulent flow.

Boundary layers around aerodynamic surfaces can be either laminar or or turbulent, and each of these has its own advantages and disadvantages. Whereas a laminar boundary layer produces less friction drag, due to the nature of its flow, it tends to have a more abrupt detachment process, transitioning to stall. Turbulent boundary layers have a smoother and easier to control stall process, and tend to stay attached to the surface longer on higher angles of attack due to its higher local velocities next to the surface and consequently higher kinetic energy [1].

The higher kinetic energy in the boundary layer, the greater its capacity to withstand adverse pressure gradients, which are the main cause of flow separation [2], showing that it is preferable to have as much kinetic energy as possible in order to delay separation. For these reasons, it is often desirable to introduce turbulence early on in the laminar boundary layer, in order to better maintain and control the flow.

Flow control devices are generally employed to delay a laminar flow, or to advance transition to a turbulent boundary layer, preventing separation in order to decrease drag and increase lift [3]. These devices can be classified as passive or active controls. Figure 1 shows different types of active controls, which are discussed in section 2 and are the focus of this article. Passive controls are briefly introduced and discussed below.

1.2 Passive boundary layer control.

Most common passive control devices consist of slots and slats, employed on the leading edges of wing sections, and vortex generators.

The slot is a fixed gap on the leading edge which allows high energy air from the lower surface to flow into the boundary layer on the upper surface during high angles of attack, increasing the boundary layer energy and delaying air flow separation. It means that the boundary layer keeps attached to the surface for higher angles of attack, generating also higher maximum lift coefficient and delaying stall [2].

The slat has the same operating principle as the slot, however with an automatic and moving arrangement. During cruise regime the slat is kept close to the leading edge by the high local pressure. At high angles of attack the slat is forced to move forward due local suction pressure on the leading edge, which opens a slot and allows the passage of airflow [2].

The vortex generator represents another passive control device that can be employed to delay boundary layer separation and keep it longer attached to the surface. As well as slots and slats, the vortex generator increases the kinetic energy of the boundary layer by creating a vortex next to the leading edge, which introduces a turbulent flow next to the surface and keeps the flow longer attached. As already discussed in section 1.1, the boundary layer must have the highest possible kinetic energy in order to prevent separation, and the turbulent flow often is preferable to the laminar flow, due to its higher velocity profiles and higher local velocities next to the surface [2].

2 Active Boundary Layer Control

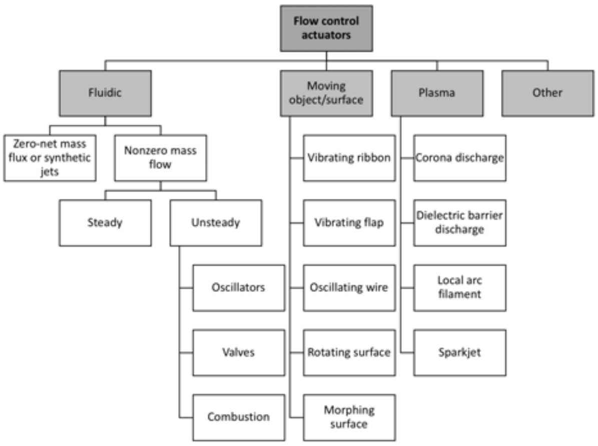

Fig. 1 . A type classification of flow control actuators based on function (according to [4].

The research on active boundary layer flow control focus mainly on reattaching/maintaining turbulent boundary layers, although there is also research in maintaining a laminar flow for longer sections of aerodynamic surfaces, by control of the *Tollmien-Schlichting* waves early on in the transition process. Active systems for the control of such flows, due to the complexity of this subject, require high-bandwidth actuators, which must be frequency tuned to adjust to cope with changing flow conditions [4]. This means that actuators for active flow control must be capable of rapidly adjusting frequency, phase and amplitude of its action to respond to complex signal waveforms [4]. As seen on Figure 1, active flow controls methods may be divided in four main categories. The first three will be briefly introduced here.

2.1 Fluidic actuators.

Fluidic actuators use fluid injection or suction to modify the boundary layer flow, ranging in scale from conventional macroscale sizes to submillimeter-scale, in the case of microjets [4]. One example of this, described by Petz and Nitsche in [5], in the injection of fluid close to leading edges of flaps, thus maintaining the flow attached to the surface. Fluidic actuators are mainly classified as:

(a) *Zero-net-mass-flux (ZNMF)*, which inject or expel working fluid in an oscillatory manner using orifices or slots, not requiring external fluid sources, but are typically limited to moderate subsonic speeds, being controlled by fast response valves, liberating pulses of fluid into or out of the flow (the control and synchronization of the valves (phase) is complicated, and they do not allow for closed-loop control) [4];

(b) *Nonzero-net-mass-flux*, which require a fluid source or sink in a steady or unsteady manner [4]. Examples of these are:

(i) *Pulsed jets*, which are a modified version of ZNMF, requiring and external fluid source [4];

(ii) *Powered resonance tubes*, based on acoustic resonance, when flow enters a closed tube and resonates, generating a combination of compression and expansion waves that reflect along the tube, being able to generate high-frequency excitation, which could potentially control oscillations on high speed flows. Although these actuators possess high bandwidth and tunable resonant frequencies, they have slow time responses, which do not allow the excitation signal to be change rapidly enough and to be phase controlled, thus not being suitable for feedback control [4];

(iii) *Combustion actuators*, which consists of a very small combustion chamber, in which the ignition of a gaseous fluid/oxidizer mixture ejects a pulsed jet, by a rapid pressure rise in the chamber, which typically lasts for several milliseconds. Experiments have been conducted with frequencies up to 150 Hz and Mach numbers up to 0.7 [4].

2.2 Moving object/surface actuators.

Mechanical actuators are designed to locally induce fluid motion [4]. May include moving surfaces (such as membranes [6]), piezo-electric flaps, shape memory alloys and electroactive polymers, and although they have the advantage of a high force to weight ratio, their performances are limited by power requirements and by working only at relatively low frequencies [3] [4].

Examples of mechanical actuators are:

(a) *Membrane actuators*, which may be excited under their surface by an array of loudspeaker coils or piezoelectric elements, for example, interacting with the flow close to the membrane in order to reduce the amplitude of Tollmien–Schlichting instability waves, using finely adjusted counter waves [6] [5];

(b) *Active dimples*, that are microfabricated using polymers, and by the application of a voltage, which causes them to buckle, produce unsteady depressions on the wing surface, which interact with the turbulent structures near the wall [4]. There is still research being made to predict the behaviour of these dimples, so that devices with appropriate size, gain and bandwidth requirements are designed [4].

(c) *Piezoelectric flaps*, which have been used successfully on multiple applications, and normally consist of piezoceramic composite beam configurations, which vibrate and have tip displacements of $\approx$ 10-100 μm on frequencies of about 1-2 kHz, and up to 1 mm for frequencies of a few hundred Hz [4]. There is a clear trade-off in gain, if higher frequencies are demanded, other than the fact that these are very susceptible to fluid loading and resonance [4].

Mechanical actuators must be carefully integrated to the wing surface, specially in the case where laminar flow is intended, as to avoid causing additional disturbances, which may introduce non-linear effects and induce TS waves, instead of reducing them [6]. Very good integration results are obtained by *membrane actuators* and by *active dimples* [6] [4].

2.3 Plasma actuators.

Plasma actuators can be used for active control by producing ionic winds of several meters per second on the surface of the structure. These actuators modify the airflow profile in the boundary layer and hence can delay or prevent transition. The advantage of the plasma actuator is that the design has no moving parts, low mass and a very rapid time response to the actuation [4].

The examples of plasma actuators, according to Cattafesta *et al.* [4], are:

(a) *corona discharge*, is a self-sustaining discharge which generally contains electrodes of very low radius curvatures, normally thin wires. These use high voltage DC power supply to produce the actuation between the electrodes. These produce localized ionic velocities of a few meters per second to energize the boundary layer and keep it attached. Depending on the voltage applied, these actuations can be pulsed or stable.

(b) *dielectric barrier discharge*, these actuators use a dielectric medium between the two electrodes to produce a more stable plasma region. These generally use high voltage AC power supply in the range of $\approx$ 15-20 kV with frequencies from 50 Hz to 20 kHz.

(c) *sliding dielectric barrier discharge*,is similar to the DBD but includes an extra electrode flush mounted on the surface, to reduce the electromagnetic effect from the plasma discharge. The frequencies are varied to obtain the desired strength of plasma.

3 Conclusion

As the field of active flow control depends on the interaction of multiple complex and diverse areas, its development correlates to individual advances on these separate areas, as well as unified studies and collaboration between them. Although many of the active control methods described here have been deeply studied, these studies were often performed in controlled conditions (laboratories and wind tunnels), frequently at slow speeds (low values of Reynolds number), so that their level of readiness has not yet reached a point where their application in civil aircraft is feasible, due to robustness, cost, reliability, certification and integration [3].

There is great optimism that active flow control will have a great impact on the aerodynamics of future aircraft. However, as mentioned above, its progress is yet on very early stages, so that much more research and effort are still required before practical implementation is achieved.

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