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Review on Progress and Application of Active Flow Control Devices - Coandă Effect on Unmanned Aerial Vehicles

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Abstract – Coandă effect can be found in virtually all aerodynamic applications, and has drawn renewed interest for various applications, among others for generating lift and maneuvering impulses to be applied for unmanned air vehicles (UAV) and micro air vehicles (MAV). These air vehicles have the potential to revolutionize our sensing and information gathering capabilities, in homeland security and environmental areas. Sophisticated unmanned air vehicles for general applications have been developed rapidly across many different industries and interested researchers. In order to carry out a task, these air vehicles have to face many different challenges, due to the MAVs small size, flight regime, and modes of operation. This has led to the development of novel platforms that move away from traditional aircraft design in order to make them more capable. A good example is the Coandă MAV which uses the Active flow control–Coandă Effect. Improved aerodynamic performance of these air vehicles can lead to fast take off and slower landing speeds that can be related to reduce noise and crash survivability issues. The investigation and research in this field is rapidly rising and there are many concepts currently being considered around the world. This report provides an overview on the state of unmanned air vehicle and introduces the techniques of Active Flow Control ACF that could be potentially used for control of UAV. Furthermore, this paper may also focuses on the review research involved with the design modification and the generated flow phenomena of Micro air vehicle MAV.

Keywords: CFD, Circulation Control, Coandă Effect, Flow Control, MAV, UAV

Introduction

The Coandă Micro air vehicles (MAVs) are unique version among many of the unmanned aerial vehicles currently deployed around the world, which do not have moveable parts. The Coandă micro air vehicles existing now a day could be related to the group of unmanned aerial vehicles (UAVs) that include fully autonomous aircraft, remotely operated aircraft and remotely piloted vehicles (Nonami, 2007). Unmanned Aerial Vehicles provide an excellent base for many aerospace applications.

A survey of previous research pertinent to the current study of the Micro Air Vehicle with Coandă effect is elaborated in this section. The Coandă effect, as an active flow control, could be applied to a conventional fixed wing aircraft and unmanned aerial vehicle to improve lift, as well as other performance parameters, by a considerable factor.

Flow control is an aerodynamic method of changing flows with the intention to accomplish a desired effect: such as enhance lift, delay of flow separation and drag reduction, noise reduction, increased combustion efficiency and so many other industrial applications, (Gad-el-Hak, 1998, 2007).

During the last 20 years, many sophisticated unmanned air vehicles (UAV) for civil and military applications have increasingly been developed all around the world. The demands for information gathering capabilities in environmental monitoring, security and intelligence are spawning the development of a smaller next-generation UAV called the Micro Air Vehicle (MAV). The operating range of these small air vehicles is only for several kilometres and during flight time can transmits spontaneous information (photos Video) back to their portable base station, (Wilson,2000). Figure 1 depicted different types of application of MAVs. The base station with several MAVs can be handled by a single person, an impossible scenario for other UAVs with larger sizes, on the basis of recent advancements in key technologies of flight control, propulsion, communications, and sensors. In order for a UAV to carry out a task, it has to overcome many challenges, due to the MAVs small size, flight regime, and modes of operation. This has led to the development of novel platforms that move away from traditional aircraft design in order to make them more capable. A good example of this type of craft is one which uses the Active flow control (Coandă Effect) to assist propulsion (Djojodihardjo & Ahmed, 2014). Focusing on the MAV design, many radially shaped (Saucer-Like) vertical take-off and landing aircraft model designs are using Coandă effect to generate the required vertical thrust to lift off the aircraft from its landing base. The principles and the performance of this system stand out as concept that needs to be elaborated.

Figure 1: Micro Air Vehicle MAV operation and Missions (Different resources)

A high indication was raised during the last few years, that Coandă effect has been given considerable considerations for circulation control technique as reported by Gad-el-Hak, 1998, 2007, Jones et al.,2002, 2005; Englar , 2005 and Kweder et al., 2011 and Djojodihardjo et al. 2011, 2013 and 2014.
Generally, the porpoise of this paper is a review on the investigates of the active flow control with applicability in aerospace, UAVs and MAVs, and to determine if the use of Coandă jets are useful in altering the aerodynamic characteristics of air vehicles will be designing for optimum performance. Furthermore this review is meant to provide updated review of Coandă MAV that have been designed, tested, and /or deployed in real missions and to indicate the applications and potential advantages of Coandă MAV over conventional MAV.

Flow control technology

The definition of Flow Control is firmly connected to the physical characteristics of flow around any aerodynamic body. Hence, Flow Control can be defined as a process to modify a flow field around the aerodynamic body, by some external means, such as aerofoil, flaps, ailerons, and other active flow controls (blowing and suction), etc., to meet some objective, (Gad-el-Hak 1998; Washburn, 2002 and Sellers et al., 2003).

The science of flow control is strongly bonded with the boundary layer theory, introduced by Prandtl in 1904. He explained the physics of the separation phenomena, and the boundary layer control through the description of several experiments. A variety of flow control techniques for aerodynamic body performance enhancement has shown breakthroughs from conventional aerodynamic constraints and achieves drastic performance enhancement. Various flow control techniques (passive or active) have been used to accomplish desired effects: examples include delay or promote transition to turbulence, prevent or induce separation; or suppress or enhance turbulence, (Bushnell & McGinley, 1989, Fiedler & Fernholz, 1990, Moin & Bewley, 1994 and Gad-el-HaK, 1996, 2007. Flow control refers to the ability to alter flows with the aim to achieve a desired effect: examples include drag reduction, lift enhancement, mixing improvement and noise suppression among many other industrial applications. Specifically, the crucial facts of all flow control technology are depicted in details in figure 2.

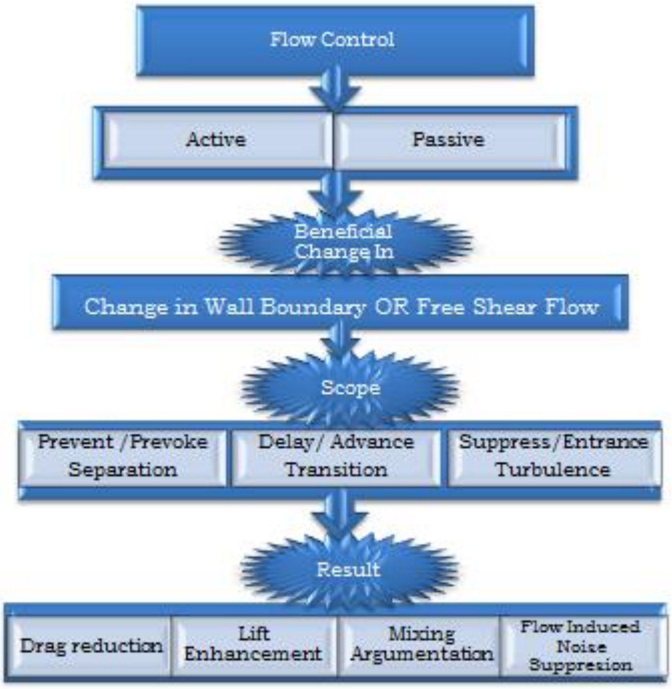


Figure 2: Flow Control operation, scope and results

Passive flow control generally involves geometry modifications to achieve a goal. Although the passive control systems are normally easy to design and simple to implement and require no external power supply, most passive control systems share some problems in practice. Walsh and Weinstein 1978; Hefner et al. 1979 and 1990; Godard and Stanislas, 2006; and Tongchitpakdee,2006, investigated these complications and verified that apart from the weight penalties, drag penalties are other drawbacks.

Active flow control is at the moment a new innovation and it is to some extent limited because of the complexity of the steady jet systems and large power requirements; details are found in Seifert et al., 1996, Duvigneau, and Visonneau, 2004, 2006. In broad, active flow control techniques can be subdivided into predetermined and interactive flow control, Gad-el-Hak (2007). Details are schematically outlined in the flow chart of the flow control as depicated in figure 3. An example of predetermined control is circulation control of wings. Lift enhancement is achieved by blowing a jet over a rounded trailing edge creating a Coandă effect and changing the aerofoil Kutta condition, “A body with a sharp trailing edge which is moving through a fluid will create about itself a circulation of sufficient strength to hold the rear stagnation point at the trailing edge”. This phenomena has been reported by, Englar and Huson, 1983; Englar et al., 1993; Joslin and Jones, 2006 and Mirkov and Rasuo, 2010. Jee et al., 2008 have used the implementation developed by Gad-el-Hak, 2007 to perform numerical simulations of a controlled aerofoil

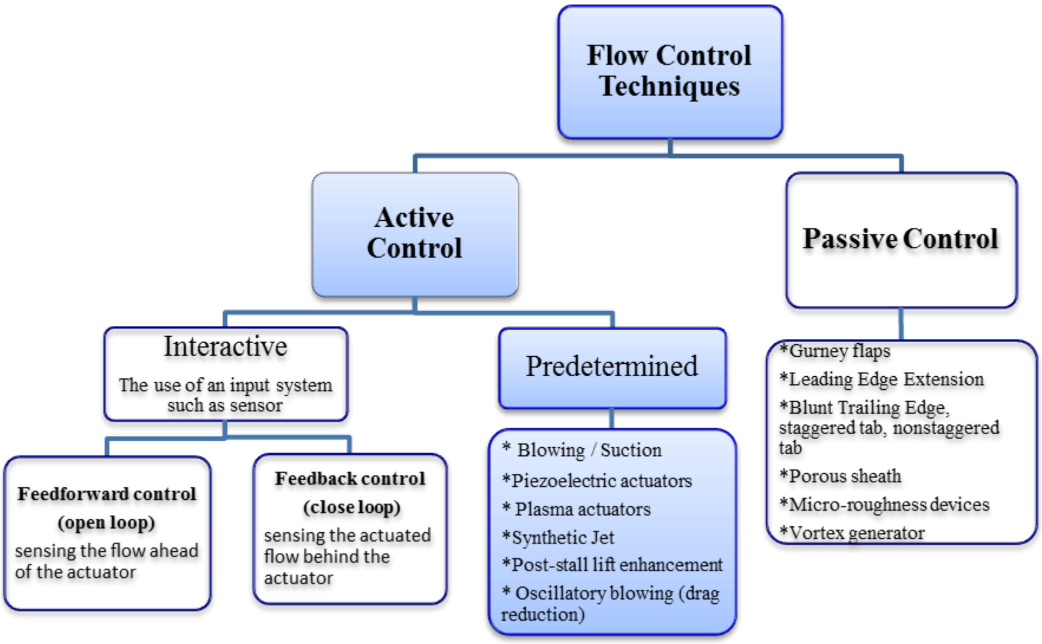
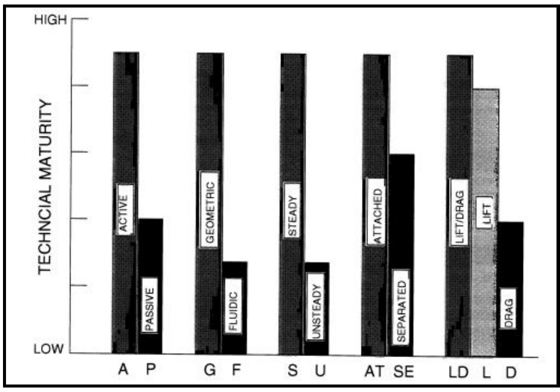


Figure 3: Classification of flow control methods (Gad-el-Hak, 2007).

More the less, there are as many as fifteen devices have revealed potential for UAVs control, wind turbine and for future quality research. It is hard to make direct comparisons between these flow control devices, since all of them operating differently, both mechanically and aerodynamically, and are at different level of maturity, figure 4a. The most well known circulation control devices used during the long time to enhance the aerodynamic performance parameters are as proposed and presented in figure 4b. The labelling scheme follows that of Wood, 1990.[1]



	Devices	Geometric (G) Fluidic (F) Plasma (P)	Leading Edge (LE) Trailing Edge (TE) Mid-Chord (MC)	Inc. Lift (I) Dec. Lift (D) Delay Stall (DS)	Steady (S) Unsteady (U)
1	Traditional Trailing-Edge Flaps	G	TE	I / D	S / U
2	Nontraditional Trailing-Edge Flaps	G	TE	I / D	S / U
3	Microtabs	G	TE	I / D	S / U
4	Miniature Trailing-Edge Effectors	G	TE	I / D	S / U
5	Microflaps	G	TE	I / D	S / U
6	Active Stall Strips	G	LE	D	S
7	Vortex Generators	G	LE	DS	S
8	Blowing and Suction	F	LE / TE	DS	S / U
9	Circulation Control	F	TE	I / D	S
10	Plasma Actuators	P	LE	DS	S
11	Vortex Generator Jets	F	LE	DS	S / U
12	High-Frequency Micro Vortex Generators	G	LE	DS	U
13	Synthetic Jets	G / F	LE	DS	U
14	Active Flexible Wall	G	LE	DS	U
15	Shape Change Airfoil	G	MC	I	S / U

Figure 4: a) mechanically and aerodynamically maturity control effectors b) circulation control devices as an Active flow control used nowadays (adapted from wood 2002)

Blowing, suction and circulation controls

The methodology of Blowing and Suction as an active control technique is to introduce high-momentum air into the boundary layer on aerofoils which will contribute in overcoming adverse pressure gradients and postponing separation. Blowing and suction, as an active flow control methods,

[1] Devices technique; geometric device (G) or a fluidic device (F) or plasma actuators (P). Device Location; near the leading edge (LE), near the trailing edge (TE), or mid-chord (MC). Device adjusts the lift curve; increasing lift (I) decreasing lift (D) delay stall (DS). Devices steady (S) and unsteady (U), (S/U) devices.

could be used at various locations of a wing for leading-edge vortices and breakdown. The most prospective positions for the use of these flow controls are at: (a) suction or blowing at leading-edge, (b) blowing at trailing-edge (c) along-the core blowing. Blowing technique employed by (Wood and Celik, 1990; Gu, Robinson and Rockwell, 1993), consequently, steady suction has been engaged with Gu, Robinson and Rockwell (1993) and McCormick, and Gursul, 1996. Several studies have been conducted to investigate the effect of trailing-edge jets on wing vortices and vortex breakdown, (Helin and Watry, 1994; Shih and Ding, 1996, Phillips, Lambert and Gursul, 2003, Shojaefard, 2005 and Wang and Gursul, 2005). A delay of vortex breakdown can be achieved by having a jet blowing at the trailing-edge which will modifies the external pressure gradient. The benefits of trailing-edge jet could be observed even in the presence of a fin, which produces a strong adverse pressure gradient for a leading-edge vortex as described by Helin and Watry, (1994). One of the technologies using this phenomenon (blowing and suction) is the co-flow jet CFJ technology, developed by Gecheng Zha et al. (2006, 2007) has shown promising results. A schematic of a CFJ aerofoil concept is shown in Figure 5.

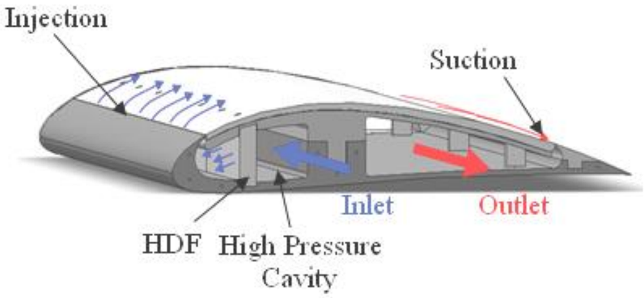


Figure 5: Schematic and concept of the co-flow jet CFJ aerofoil, Helin, and Watry, (1994)

However, Circulation control (CC) is one concept derived from conventional blowing and suction research. Circulation control is one type of the active flow control, which is currently receiving significant consideration since it is a very operative method of producing ultimate lift coefficients necessary during take-off and landing. The Circulation control wing (CCW) has been under an extensive numerical and experimental investigations over many years (Liebeck, 1978; Englar and Huson, 1983; Englar et al., 1993; Englar et al., 1994; Moin and Bewley, 1994; Gad-El-Hak, 1998; Englar, 2000; Gad-El-Hak, 2007; Van Dam et al., 2007). For more effective designs of CCW, the trailing edge of the aerofoil was made to have a curved rounded edge with a larger radius. Circulation controls is implemented by tangentially injecting a jet sheet over a curved surface such as rounded wing trailing edge which energizes the boundary layer, increasing its resistance to separation and remain attached along the curved surface due to the Coandă effect (a balance of the pressure and centrifugal forces) and causing the jet to turn without separation. One draws of this modification was a high drag penalty while the jet was off. The solution was introduced by Tongchitpakdee (2007), by making the lower surface of the trailing edge a flat surface, while keeping a highly curved upper surface. Figure 6 shows a typical traditional CC aerofoil with a rounded trailing edge as given by Englar (2000) and Jones and Englar (2003).

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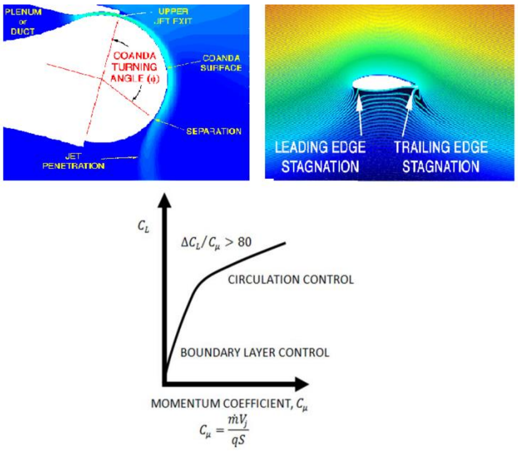

Figure 6: Basics of Circulation Control Aerodynamics, Englar (2000)

Coandă effect

Coandă Effect is a classic phenomenon in fluid mechanics and one of the fundamental discoveries of the Romanian inventor Henri Marie Coandă (1886 -1972). Henri Coandă was a Romanian inventor, aerodynamics pioneer and the designer and the builder of the world's first jet powered aircraft, in 1910, (Coandă, 1932). Coandă has used this effect as a wing circulation control in the 1930s, (Coandă, 1935). He came to the conclusion that the Coandă effect is due to a balance within the jet sheet between the pressure gradient normal to the surface and the centrifugal force caused by the streamline curvature. Coandă effect can be defined as that “the tendency of a fluid jet to attach itself to a curved surface or to be attracted to a nearby surface flaps or aerofoil”, (Bradshaw, 1990; Djojodihardjo & Ahmed, 2014). The profile has being characterized by a significant asymmetry as depicted in Figure 7.

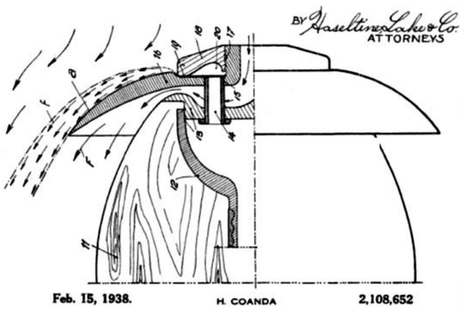

Figure 7: Henri Coandă propelling device, Coandă (1938)

Coandă effect has always been referred to in the consideration of various flow control methods to enhance aerodynamic performance, i.e. to enhance lift, reduce drag, and delay stall at higher angle of attack, (Djojodihardjo & Thanagarajah, 2014). The technique of these system, engine thrust, or exhausted air, is directed across a wing surface or out the trailing edge to help the flow stays attached to Coandă Curved surface and generate additional lift.

Studies carried out thus far by Jones & Englar (2003), Kweder (2011), Drăgan (2013), Djojodihardjo (2013) and Djojodihardjo & Ahmed (2014, 2015) could enable us to identify a “Coandă jet as a relatively thin and slightly viscous jet flowing over a smooth curved surface and within the thickness of the prevailing boundary layer over that surface”. A detail of such jet flow is indicated in Figure 8.

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The Coandă jet could be used for providing flight control to include stabilization and manoeuvring, potentially removing the need for moving control surfaces.

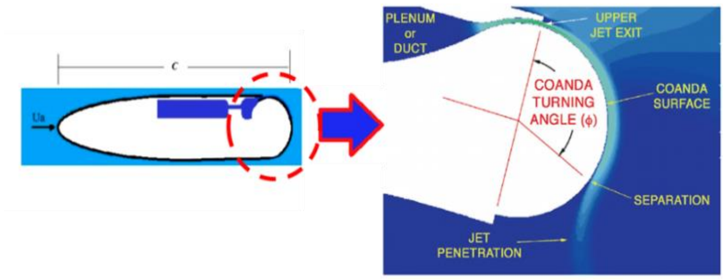

Figure 8: Behaviour of Coandă jet effect over curved trailing edge surface, (Jones *et al.*, 2005).

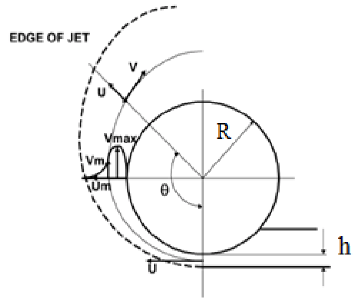

Figure 9: Schematization of Newman's case study.

In 1936, Canada Effect was formulated in relation with three different phenomena associated with it and according to the studies carried out over the previous years, (Keller, 1957: Bradshaw, 1973 and Djojodihardjo, 2013). These are a combination of three effects: first is the tendency of a fluid jet initialized tangentially on a curved surface to remain attached to that surface. Second, the ability of a free jet to attach itself to a nearby surface and third, the tendency of jet flows over convex curved surfaces to entrain some of the surrounding free flow and to flow more rapidly than that of plane wall jets.

The scientific studies about the Coandă effect are characterized by fundamental studies by Von Glahn (1958), Roderiek (1961), Newman (1961) and Benner (1965). Newman (1961) investigated a two-dimensional, uncompressible, and turbulent jet flow, flowing around a circular cylinder, (Figure 9). Coandă adhesion to a curved surface can be demonstrated as a consequence of the balance of the forces applied to the fluid, which are in equilibrium: the radial pressure force and the centrifugal force, (Newman & Carpenter, 1961; 1997). The main geometric parameters of the flow are the slot width (h), separation angle (θ) and the radius of curvature (R) and the dynamic quantities involved in the system as depicted in figure 9. Other related parameters are Reynolds number Re and the pressure differential (supply pressure p_s− atmospheric pressure p_∞).

The Coandă effect can be attributed to the notion that if a thin film jet is positioned close to a wall, pressure forces change the path of the fluid elements, due to the low pressure between the jet and the surrounding pressure (Bernoulli principle) which then results in forces acting on the jet towards the solid surface. Since the wall prevents fluid inflow into the area between the jet and the wall, this area will have less pressure than the area away from the jet. Due to the momentum transport from the jet to the stationary or slowly moving fluid, also from the effect of viscosity, the flow in the vicinity of the jet is accelerated. The emerging pressure gradient normal to the wall generates a force, which moves the jet flow towards the wall. However, the surface pressure along the curved wall away from nozzle rises and gradually equates the ambient pressure. For such condition a detachment will occur between the curved wall and the fluid jet. Hence, Newman (1961) has defined the relation among the separation angle θ, shown in Figure 9, and the dynamic quantities involved in the system and main geometric parameters of the flow as:

$$\theta_{sep} = 245 - 391\frac{h / R}{1 + 1.125h / R} \tag{1}$$

A comparison of the separation angle determined through the various empirical relations method as function of the jet slot thickness to body radius ratio (h/R) ratio is depicted in the figure 10. The Coandă effect will move the stagnation point aft, and delay the separation (see figure 10). Eventually, the adverse pressure gradient along the surface will increase, and the momentum within the jet and the boundary layer will decrease, hence this adverse pressure gradient is what eventually causes the jet to separate and leave the surface.

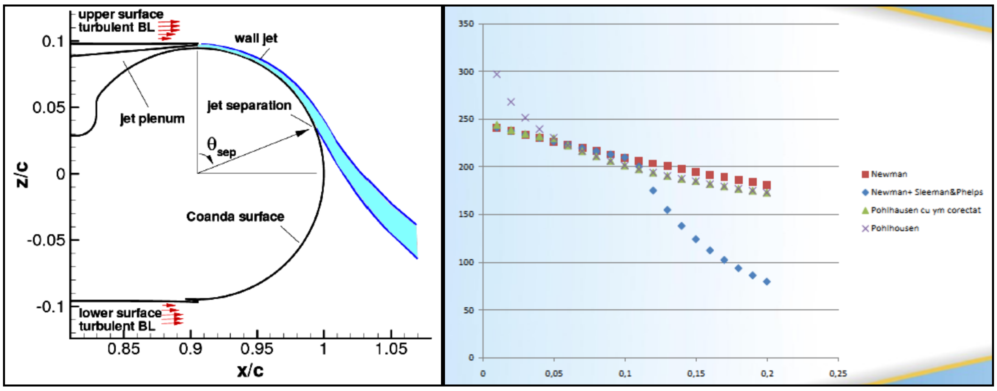

Figure 10: a) Coandă flow over aerofoil TE and b) separation angle as of function of (h/R) ratio determined through various methods

The feasibility and the benefits of using Coandă techniques to enhance aerodynamic performance of an air vehicle and to location of the separation point can be assessed by using the Coandă jet momentum coefficient, C_μ (Mamou and Khalid, 2007; Djojodihardjo, 2011 and 2013), which are defined as:

$$C_\mu = \frac{\dot{m} V_{Coand\breve{a}-jet}}{\frac{1}{2}\rho_j V_\infty^2 A_{ref}} \tag{2}$$

where $\dot{m}$ is the jet mass flow rate, $V_{Coand\breve{a}\text{-}jet}$ is the Coandă jet velocity, ρ_∞ and V_∞ *are* the free stream density and velocity respectively, and *A* is the aerofoil plan form area.

There are a few near term applications of active flow control and biologically inspired technologies to flight vehicles, most of the technologies being researched have significant issues still to be addressed before they can be used regularly. For instance, some of the major barriers to the advancement of active flow control are inadequacies in energy efficient flow control actuators with sufficient authority and size and the need for small, robust sensors to measure time-dependent phenomena. Moreover, there is generally a lacking understanding of unsteady and non-linear aerodynamics and consequently, analytical models to predict the interaction of the fluid mechanics with actuation have not been completely developed or validated.

The active flow control promise tremendous advances in air vehicle performance and capability, especially when new vehicles are conceived around these technologies. Active flow control is of particular interest if the flow has to be optimized for diverse conditions and objectives. The objective and the efficiency of a flow control device has always to be evaluated in a global context when considering a practical application.

Lately, the flow control is primarily focused in four general areas:

- fundamental tool development,
- performance enhancement,
- maneuvering control and
- noise attenuation.

Research on nozzle demonstrated that a two parallel same speed and symmetric turbulent free streams, acting on symmetric Coanda surfaces system is not influenced Coanda surfaces and produces a straight synthetic jet. Any modification of the symmetry both in geometry and in fluid momentum can produce a deflection and that this deflection increasing the asymmetry or increasing the fluid dynamic asymmetry in terms of relative variation of the momentum between the two primary jets which forms the synthetic jet.

Some actuation concepts in active flow control are synthetic jets, pulsed jets, active or vibrating small-scale structures and glow discharge or plasma devices. In many cases the major breakthroughs will probably be realized through better actuator and sensor packaging. Feasible routes using oscillatory flow-control systems (flow instability) as an efficiency enhancement tool are discussed as an emerging means to explain the physical phenomena of active flow-control and as a tool for control law design and development.

Most often actuators are used that blow air from an orifice or a slot in the surface, either as steady or pulsed flow. Other actuator types include electromechanical and mechanical. The fast development of Micro Electromechanical Systems and their application in Flow Control System opens the perspectives of designing practical wing load control systems based on fluidic actuators, modifying local aerodynamic loads by inducing changes to flow. The potential advantages in comparison to classical devices include potentially shorter reaction time because of avoiding the necessity of moving large surfaces against high dynamic pressure, which is important in conditions of fast-changing loads in turbulent atmosphere.

A relatively new type of actuator used for flow control are dielectric barrier discharge (DBD) plasma actuators, which are offering several benefits, such as fast reaction times due to the absence of mechanical parts. They induce a wall parallel jet by ionizing the air and thereby generating a plasma through an alternating high voltage applied to them. The design, construction and commissioning of

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an Unmanned Aerial Vehicle (UAV) for flow control experiments with plasma actuators under realistic flight conditions is considered the current and future direction of active flow control devices. Active flow control techniques can be implemented through various methods e.g., continuous blowing, continuous suction , pulsed blowing , oscillatory blowing and suction , vibrating ribbons , wall oscillations and net-zero mass flux actuators. Desired results are achieved by either removing the low energy carrying fluid from the boundary layer or by increasing the boundary layer momentum. Net-zero mass flux actuation and pulsed blowing additionally introduce vertical structures into the flow, which influence the mixing of the slow moving boundary layer with the free stream.

The leading edge pulsed blowing showed a strong dependency of the actuator effectiveness on the jet momentum and the pulser frequency. The leading edge pulsed blowing had delayed the flow separation over the air foil on the other hand, the trailing edge jet flap was capable of generating significant roll moment at realistic jet momentum coefficients. The trailing edge jet actuators were also able to augment lift and demonstrate the roll control authority at low angle attacks at a cruising speed.

The Coandă effect has many potential applications for both aircraft and ground vehicles, as well as high lift devices, due to its capability to entrain a large mass of air and bend it towards the ground to gain lift for the aircraft wing or wind turbine application. Moreover it has been used in other areas such as in marine technology, automotive industry, air conditioning system, medicine (as a ventilator), and meteorology. In the last decay the Coandă's legacy was appreciated by many investigators around the world, mostly by modification, developments, and patents on MAVs and UAVs.

The interesting capabilities of the Coandă effect were implemented on many other aircraft such as the Antonon Izdelie181, Custer Channel Wing ,Englar, (2002), West Virginia University (WVU) flight demonstrator "loth 1976", Navy demonstrator aircraft "A-6/CCW" (1979) (Harris, 1981), Boeing YC-14(1976), Antonov An-72 "Coaler" (1977), Douglas YC-15, and C-17 "Globemaster III" (1991).

Figure 11: Coandă Effect implemented on aircraft a) Antonov Izdeliye 181 b)WVU Flight Demonstrator c) The Navy A-6/CCW demonstrator aircraft d) Boeing's YC-14 (1976) (AMST) e) The Antonov An-72, and f) The Boeing C-17 Globemaster III

Nowadays, Coandă effect is used mainly in helicopters as an anti-torque system that replace the rear rotor, as in NOTAR system.

Figure 12: The NOTAR system

Unmanned aerial vehicle UAV and micro air vehicles MAV

Unmanned Aerial Vehicle UAV

The first successful heavier-than-air flight test in human history was carried out by the Wright brothers, Orville and Wilbur, on 17 December 1903, using a powered vehicle, Pad field and Lawrence. In June 1914, another attempt by Lawrence Sperry together with his assistant/technician Emil Cachin in France-carried out a public demonstration of an aircraft whose control surfaces were managed by an elementary autopilot system, governed in turn by a gyroscope integrated in the fuselage. Since then, unmanned aerial vehicles have been called by many different names (pilotless aircraft, remotely piloted-vehicles (RPVs), drones, UFO, etc.) Unmanned Aerial Vehicles (UAVs) according to a widely accepted definition published in the US Department of Defence Dictionary of Military and Associated Terms can be considered as:

“A powered aerial vehicle that does not carry a human operator, uses aerodynamic forces to provide vehicle lift, can fly autonomously or be piloted remotely, can be expendable or recoverable "U.S. Department of Defence.

Nowadays, UAVs may have different degree of ‘automatic intelligence’ according to their application’s and missions. Figure 13 depicted the UAV control system classification, (Yenne 2004).

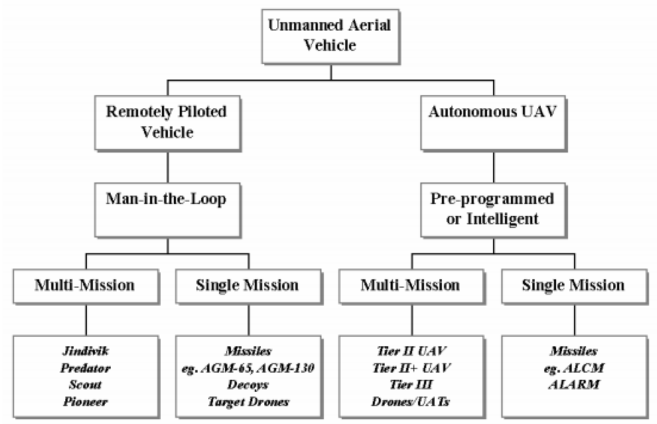

Figure 13: UAV Classifications (Lax1996)

Most of the UAV systems developed over the last 20 years have been presented in several publications. Among those, one of the first is the review made by Howard and Kaminer in 1995. A more recent, extensive and detailed gallery can be found instead in the 2005-2030 Roadmap written by Cambone et al. (2005). They are very many uses to which these UAVs are, or may be, but, the most obvious uses in both military and civilian sectors being the following:

Table 1: UAVs applications in Civilian and military sectors

Civilian uses	**Military uses**
Airborne photography still, video, film, etc.	Shadowing enemy fleets
Agriculture crop spraying and herd monitoring and driving	Decoying missiles by the emission of artificial signatures
Land monitoring and conservation pollution	Electronic intelligence
Customs surveillance for illegal imports	Relaying radio signals
Coastguard search and rescue, sea-lane monitoring	Guarding of ports from offshore assaults
Police authorities searching missing persons, safety surveillance, incident monitoring	Placement and monitoring of sonar buoys and other forms of anti-submarine
Forestry fire detection, fire incident control	Electronic intelligence
Local authorities survey, disaster control	warfare
Electricity power line inspection, oil and Gas supply companies, pipelines security	Intelligence, surveillance, and reconnaissance (ISR) platform
Information services, news information and photos, feature pictures, e.g. wildlife	Monitoring contamination of nuclear, biological or chemical (NBC).
Lifeboat incident investigation, guidance and control	Airfield base security and damage assessment
Ordnance survey aerial photography for mapping	Target designation and monitoring
Weather-related services, sampling and analysis of atmosphere for forecasting, etc.	Location and destruction of land mines
Traffic monitoring, road traffic control	Longer range, higher altitude surveillance
Water boards reservoir and pipeline monitoring	Radar system jamming and destruction
Rivers course, flooding, and pollution control	Elimination of unexploded bombs
Survey organizations geographical, geological and archaeological survey.	

Micro air vehicles MAV

It is true that distinguishing between UAVs and MAVs is significantly challenging to trace a clear demarcation line and, within MAVs, between “small”, “mini”, micro", “Nano" vehicles as they are often referred to across the literature. As has been highlighted by Mueller and DeLaurier, 2001; no researchers, so far have provided a clear and easy-to-use classification system yet. Most of the researchers and firms involved in MAVs design seem to adopt their own flexible and malleable definitions. The Defence Advanced Research Project Agency (DARPA) dominated definition of the MAV is;

> “Micro air vehicles (MAV or μAV) are defined as semiautonomous airborne vehicles that are “six-degree-of-freedom aerial robots, whose mobility can deploy a useful micro payload to a remote or otherwise hazardous location where it may perform any of a variety of missions, including reconnaissance and surveillance, targeting, tagging and bio-chemical sensing.

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Small and Micro UAVs can potentially operate in urban or cluttered environments which require a high manoeuvrability. In addition to the desired reduction in size and weight, it is required to reduce the minimum speed of the UAV. This will enhance manoeuvrability (Shyy et al., 1999), reduce the kinetic energy of the vehicle, and improve the durability and impact behaviour (Viieru et al., 2006). MAVs are categorized into four groups according to their concept and types, for instance, fixed wing, Rotary wing, flapping wing, and hybrid MAV as illustrated in figure 12,(Grasmeyer and Keennon, 2001; Mueller and DeLaurier, 2001; Singh et al., 2005; Viieru et al., 2006 ; De Croon et al., 2009; Nakata et al.,2011 and Yang, 2012).

The range of applications for true MAVs is not yet comparable to the diversity of tasks in larger UAVs. The advantages of small size MAVs can be accountable in teams of requirements such as cost effective (Bronz et al., 2009), high manoeuvrability, low hazard potential (in terms of kinetic energy).The last two requirements are essential when operating in the urban environment or in close proximity with humans and creatures,(Green and Oh, 2009); (Vermeulen et al., 2013). Currently, the main farm duties for MAVs are mainly related to surveillance, chemical detection, damage assessment inside cities and buildings (Sarris, 2001). In addition to the enhanced manoeuvrability, these features render MAVs generally very attractive.

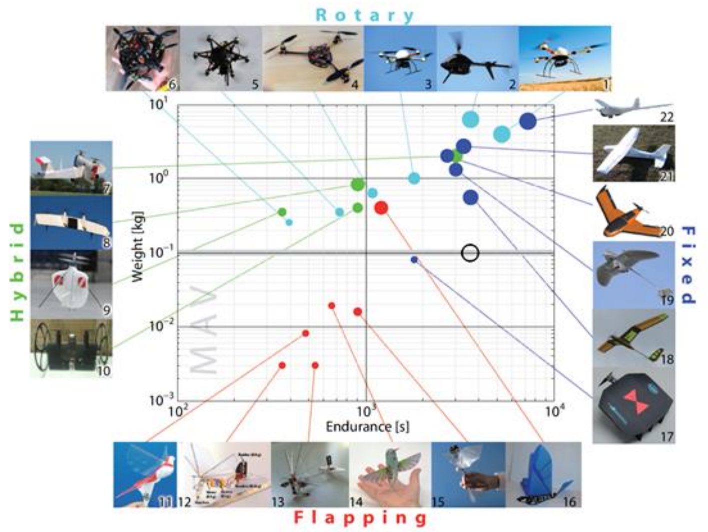


Figure 14: UAVs and MAVs concept, and the relation of take-off weight, endurance and size (William Thielicke, 2014)

Coandă micro air vehicles (MAVs)

Capabilities and applications

Coandă Micro air vehicles (MAVs) are unique version among many of the unmanned aerial vehicles currently deployed around the world, which do not have moveable parts. The Coandă micro air vehicles existing nowadays could be related to the group of UAVs that include fully autonomous aircraft, remotely piloted vehicles, and remotely operated aircraft (Nonami, 2007). Coandă Micro air vehicles provide an excellent base for many aerospace applications. These air vehicles have the potential to mature our sensing and the capabilities to information gathering in environmental monitoring and homeland security areas.

For Coandă MAVs, the performance in hover should be at least equal to that of a helicopter and in forward flight be at least equal to a fixed wing aircraft, Djojodihardjo and Ahmed (2014, 2015). This puts the concept in direct competition with the flapping wing MAVs or with the ducted fan MAVs.

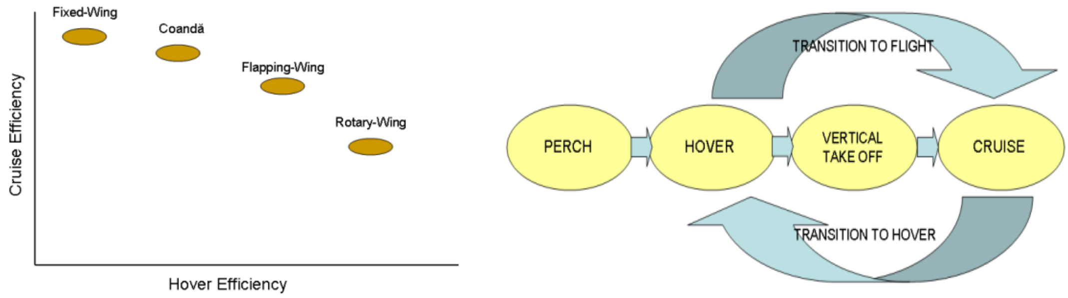


Figure 15: a) An impression of the possible Coandă MAV qualitative performance in comparison to other flight vehicles (Djojodihardjo and Ahmed (2015), as an adaption from Schroijen and Van Tooren, 2009); b) Flight Manoeuvring Structure (Djojodihardjo and Ahmed (2015), as an adaption from Frank and McGrewy, 2010).

In contrast, Coandă MAV can peach, hover, and examine a field area, rotating to pan the cameras in different direction and altering zooming focus.

A classic configuration of Coandă MAV usually referred to as a flying saucer like MAV (or a flying disc) is a term used to describe air vehicles with a disc or saucer-shaped body see Figure 16.

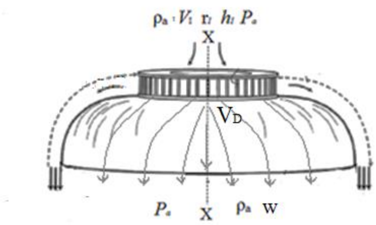


Figure 16: Schematics of Coandă MAV

Coandă MAV flying saucer has all the benefits of a conventional helicopter, and the additional benefit of a smaller footprint due to the elimination of a tail-rotor. In addition to these general features, there are many aspects of this platform configuration which make it an excellent choice as an urban MAV. Coandă effect offers greater potential at a micro-air vehicle scale with regard to fundamental performance parameter "L/D ratio" (Saeed, 2012; Djojodihardjo et al. 2013). Due to its configuration, Coandă UAV has the advantage of surviving low speed impact with the ground, buildings and other fixed objects, and has a better approach in landing, with the payload unaltered, in very different weather conditions or locations, even if the approaching manoeuvres are not well conducted, (Collins,2006; Hatton,2007 ; Barlow,2009; and Djojodihardjo and Ahmed, 2015).

In last few years, the interest on Coandă Micro air vehicle has grown remarkably due the various areas of application especially in civilian fields such as aerial imaging, monitoring, and communications etc.

These features render Coandă MAVs generally very attractive. Future observation, may put the tasks for Coandă MAVs to be dominantly for surveillance mission, damage assessment and chemical detection inside cities and buildings, similar to the currently scope of the conventional MAVs (Sarris, 2001). Further expectation for Coandă MAV in synergy with the developing technology, certainly will be capable for other missions that are currently the preserves of bigger UAVs. Coandă UAVs shall be able to carry out a large variety of missions such as: Forest and crops monitoring, fire fighting management, Emergency rescue, Law enforcement (Police, Civil Security), Border and Coastguard security, Oil, gas industry pipe lines and electricity towers security, infrastructure, network and Environmental monitoring, fishery protection and aerial inspection and photography, mapping and Surveying etc.

Coandă MAV background and progression

In early 1910, the world first airplane, equipped with a jet reactive propulsion system in the world, was designed and built by the aerodynamics pioneer Henri Coandă, a revolutionary plane of the 20th century, and the first to use the phenomena of Coandă effect, (Coandă -1910 Aircraft). This plane exhibited at the Grand Palais on Champs-Elysees in Paris, hosted the second International Aeronautical Exhibition in 1910, See figure 17.

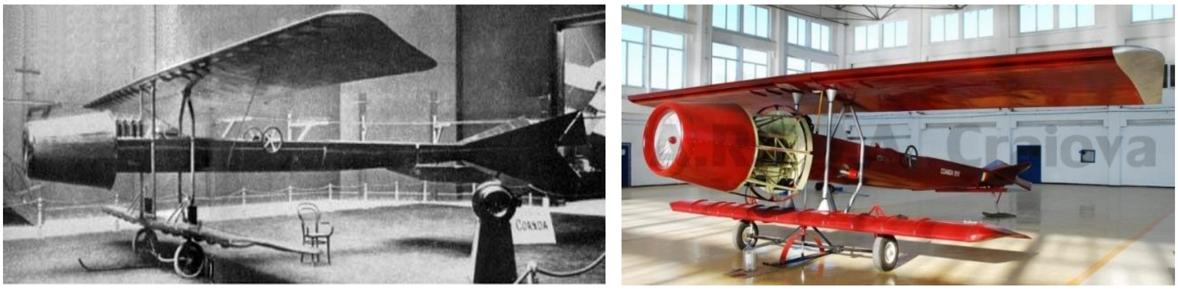


Figure 17: COANDĂ-1910: Henri Coandă built and flew the world's first jet aircraft "red airplane without a propeller" ((Henri Coandă -1910 Aircraft)

In 1952, another attempt to design a Coandă effect aircraft was proposed by John Carver Meadows Frost, a British aircraft designer, to design a vertical take-off landing (VTOL) aircraft, called "VZ-9 Avrocar". Lift and thrust of the Avrocar was intended to be produce by exploiting the Coandă effect by using single "turborotor", blowing exhaust out the rim of the disk-shaped aircraft to provide anticipated VTOL-like performance, (Winchester, Jim, 2005). In late 1961, the famous American-Canadian saucer Avro VZ-9V, figure 18 a, at the James Forrestal Center, Princeton University, New Jersey, was tested and it had been beyond control when more than three feet above the ground, Rose et al. (2006).

Astor kinetics-Dynafan made a VTOL Flight unit, designed by Miller in 1964, (Miller et al. (2005)) that was using the "Coandă effect" for vertical thrust. This invention relates to the new and useful improvement in VTOL flight units, figure 18b, aiming to provide a new and improved flight unit, having means therewith for creating a combination of different lifting forces sufficient for sustained vertical and horizontal flight.

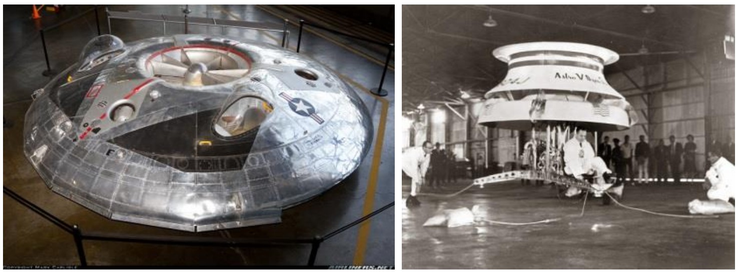
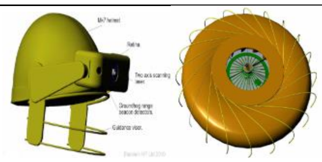
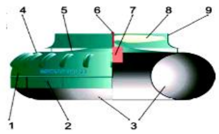


Figure 18: Coandă effect air vehicles a) Avrocar at the National Museum of the US Air force b) the Astro Kinetics Corporation VTOL

After 2000, a new class of aerial vehicles using mainly the Coandă effect, were developed by some aeronautics inventors such as Collins (2002), Geoffrey Hatton (2002) and Naudin (2006), or companies as GFS Projects Ltd (French company), AESIR Ltd (British company) and also a Romanian academic consortium, through MEDIAS project. These aerial vehicles named, the Coandă UAVs. It is unusual in terms of VTOL UAVs because it requires only one motor and propeller and has no external moving parts which means that collisions are much less of an issue. It utilizes the Coandă Effect to change the direction of the air flow from horizontal as it leaves the duct to downwards using only the UAV's curved exterior. In the last decade, inspired by Coanda legacy, aroused in Europe a wave of new UAVs.

Table 2: Summary of Coandă UAVs developed, constructed for test or proficiently used according to date of performance.

Name of Air vehicle	**Manufacturer, Year**	**Details**	**Models type**
Aerial Flying Device	Blumlein HF Limited UK 2002	A nonconventional Coandă airspace platform MAV. An oval-shaped body with a ducted propeller on top.	
Coandă disc UAV with disk gas turbine(DGT)	Blumlein HF Limited UK 2007	Coandă disc unmanned air vehicle with the Contra power unit, torque equalized disk Gas turbine Engine turbine (DGT) engine technology. Eliminate body rotation about its vertical axis	
Sweeper a UAV buried munitions location subsystem	Robert Collins supported by Middlesex University 2010	Coandă MAV, two subsystems – "Groundhog", which is a small, less than 75cm diameter disk UAV, relying principally on vortex and wall attachment. "Retina"- a helmet mounted laser designator.	
Series of Coandă effect MAVs GFS 01-05	Geoffrey Hutton (Geoff's Flying Saucers) GFS Projects Ltd UK, 2002-2007	Saucer-shaped aircraft prototypes, capable of flying outdoor, no stability problems. Most are octagonal shaped, with four control flat flaps. Patent, GB 2,424,405 /23.03.2005, ("Craft having flow-producing rotor and gyroscopic stability").	
GFS-UAV (N01A- and N02)	Jean-Louis Naudin, GFS projects Ltd, France &UK, 2006	Various l prototypes of Coandă MAVs, based on the Geoff Hatton' design. Propelled by an electric engine and utilized the Coandă effect. UAV N-01, 60cm diameter, 533g total weight UAV N-02, 1 m diameter,1800g total weight	

MEDIAS	Florin Nedelcut & researchers from Galaţi, Iaşi & Bacău, Romania 2008	Produced a new version of Coandă MAV (VTOL), hybrid, modern, non-polluting, manoeuvrable, safe to the environment and people. Electrically driven propeller; optional solar energy and helium inflatable chamber	
EMBLER	AESIR Ltd, Private company, UK, 2009-2010	60 cm diameter, with an improves electric engine, lighter carbon fibber airframe, military support MAV.	
VIDAR	AESIR Ltd, 2009-2010	Small Coandă UAV, 30cm diameter, man portable craft designed to provide surveillance and situational awareness inside buildings. 15 minutes of flight time. It weighs 400g total weight with 100g payload	
ODIN	AESIR Ltd 2009-2010	Coandă effect VTOL-UAV, (1.5m diameter) powered by Wankel Rotary internal combustion engine, weighs up to 20kg (maximum payload 10kg), 60 min. endurance	
HODER	AESIR Ltd 2009-2010	Heavy lift Coandă effect VTOL-UAV, cargo transport and resupply vehicle, multi-engines, 1ton payload for up to eight hours . 1.5 ton of weight	

Today, Coandă effect is used mainly in helicopters as an anti-torque system that replace the rear rotor, as in NOTAR system. By using this technique, it can be said that the dangerous tail rotor of the helicopter has been removed by a special and safer nozzle uses the Coanda effect. Most of investigations carried out include modification on the propulsion system as well as on the controls for better performance, manoeuvrability and more efficient hover-capable MAVs.

A new lift system for Vertical/Short Take-off and Landing (V/STOL) aircraft shown in Figure 19 was explored in Djojodihardjo et al. 2011 could be one of the future directions for active flow controls. The conventional gas turbine offers the most promise for a power unit for this class of UAV but being generally of a cylindrical configuration they are not best suited. The Coandă propulsion system might be able to provide both an efficient cruise phase and hovering capability. The performance in hover should be at least equal to that of a helicopter and in forward flight at least equal to a fixed wing aircraft. This puts the concept in direct competition with the flapping wing MAVs, however the Coandă propulsion concept could benefit from the reduced number of moving parts.

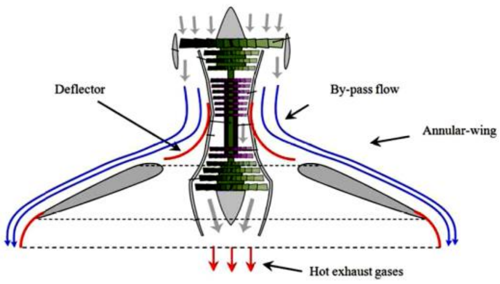


Figure 19 Annular-wing around an integrated model of turbofan (Djojodihardjo, 2011)

Until now, disk UAVs have not been advocated for use in hostile theatres due to a number of factors such as: limited endurance offered by electric power units, high noise signature associated with internal combustion engine power units and lack of automatic attrition avoidance strategies due to mission endurance limitations.

The research on the development and perfection of the Coandă UAV continue nowadays with multiple investigations in different sectors to cover, such the propulsion system , the controls, profile shape , jet nozzle configurations and other related issues.

Conclusion

Progress and development of Circulation Control of Aerodynamic Surfaces, with particular reference to circulation flow control and Coandă effect have been reviewed and assessed, in view of their features and capabilities addressing requirements and trends of modern aircraft. In this conjunction, related and selected inventions that have been built are also reviewed and assessed. The main objectives are to gain an in-depth insight on the fundamental principles of various Circulation Control Techniques, with particular attention to Coandă effect, its feasibility, and practicability and to identify salient features essential for its optimal utilization. The Coandă effect principle, analysis of the flow circulation control using Coandă effect and various uses of Coandă effect in UAVs and MAVs, has been discussed. The Coandă effects are encountered in virtually all aerodynamic applications and found many applications in engineering. The Coandă effect application in MAVs would certainly have an excessive impact. A large review of the theoretical and applicative study on Coandă effect to fluid jet deflection has been presented. Many solutions have been historically developed to ensure Coandă deflection of a flux over a curved wall. It is well known that a fluid jet in contact with a curved surface tends to continue bond to that surface, according to forms and methods that are still today the object of scientific research. This phenomenon is defined as the Coandă effect, In particular the large bibliographic presented in this paper constitutes an important part of a Coandă Effect related activity which has produced a series of unmanned aerial vehicle UAVs and micro air vehicles MAVs, that are utilized Coandă effect in its best form. Coandă MAV is a powered aerial device able to ascend, descend, and move in any horizontal direction. The device may have a body of circular, oval or polygonal plan form with a convex curved upper surface. Air above the aerial device is drawn axially into a radial disk fan which is powered by a motor, and accelerated radially over the upper surface of the body and which attaches by Coandă effects to the upper surface resulting in lift being imparted to the aerial device. A motor torque cancellation and steering device is included as well as a localised air stream detachment means, which controls lift and horizontal propulsion. Coandă effect is an important fluid mechanics phenomenon that has not yet used at its full potential and capabilities. Coandă Effect applications developed so far proved to be very efficient from energetic point of view.

References:

Aesir Ltd. (2009), *Explanation of the technology. Retrieved from AESIR Unmanned Autonomous Systems*: Retrieve from http://www.aesir-uas.com/technology.htm

Barlow, C., Lewis, D., Prior, S.D., Odedra, S., Erbil, M., Karamanoglu, M., Collins, R.,(2009) Investigating the Use of the Coandă Effect to create novel unmanned aerial vehicles, *In International Conference on Manufacturing and Engineering Systems Proceedings*, number ISSN 2152-1522, pages 386–391.

Benner S.D. (1965), The Coandă effect at deflection surfaces widely separated from the jet nozzle, *University of Toronto, UTISA Technical Note* no. 78.

Bradshaw, P., (1990), Effects of streamline curvature on turbulent flow, *AGARDograph AG*-169

Bronz, M., Moschetta, J. M., Brisset, P. and Gorraz, M. (2009), Towards a long endurance MAV. *International Journal of Micro Air Vehicles* 1(4): 241–254

Bushnell, D.M., and McGinley, C.B., (1989), Turbulence control in wall flows," *Annu. Rev. Fluid Mech*. 21, pp. 1-20.

Cambone, S., Krieg, K., Pace, P., and II, L. W.(2005), Unmanned Aircraft Systems Roadmap 2005-2030. *Tech. rep*., U.S. Department of Defense, Office of the Secretary of Defense.

Collins, R. (2008), Unmanned Coandă disk aircraft system platform. Retrieved 19 October 2009 from http://www.createthefuturecontest.com/pages/view/entriesdetail.html?entryID=1961#at.

Collins, R. J (2010), *Sweeper*, Retrieved from http://www.diseno-art.com/news_ content/2014/01/ boeing -yc-14-prototype-stol-aircraft/

Collins, R. J. (2003), Aerial flying device. U.K. Patent GB 2,387,158, Oct.8, 2003.

Collins, R. J., (2007), Explore gas turbine engine technology (the Contra).

De Croon, G., De Clercq, K., Ruijsink, R.; Remes, B. and De Wagter, C. (2009), Design, aerodynamics, and vision-based control of the DelFly. *International Journal of Micro Air Vehicles* 1(2): 71–97.

Department of Defense, (2005), Unmanned Aircraft Systems Roadmap 2005- 2030, Office of the Secretary of Defense, August 2005.

Djojodihardjo H, Hamid MFA, Basri S, Romli FI, Abdul Majid DLA.(2011), Numerical simulation and analysis of coandă effect circulation control for wind-turbine application considerations. *Journal IIUM Engineering*, 2011; 12: 51-58.

Djojodihardjo H, Hamid MFA, Jaafar AA, Basri S, Romli FI, Mustapha F, et al. (2013), Computational study on the aerodynamic performance of wind turbine airfoil fitted with coandă jet. *Journal of Renewable Energy* 2013; Article ID 839319, 17 pages; 18(1):51-58

Djojodihardjo H. and Thangarajah N. (2014), Research, development and recent patents on aerodynamic surface circulation control-A critical review" *Recent Patents on Mechanical Engineering*, pp. 1-37.

Djojodihardjo H., Ahmed R.I. (2014), An Analysis on the lift generation for Coandă micro air vehicles" *IEEE, ICARES conference proceeding*, Yogyakarta, Nov. 2014.

Djojodihardjo H., Ahmed R.I., Abu-Talib A.R. and Mohd-Rafie A.S. (2015), Analytical and CFD visualization studies of Coandă MAV," the 13th Asian Flow Visualization Conference, Novosibirsk, June2015, pp.15-18.

Djojodihardjo H., and Abdul Hamid M.F. (2013), Computational study on the influence of Coandă jet on airfoil two dimensional case, *28TH International Congress of the Aeronautical sciences*.

Duvigneau, R. and Visonneau, M. (2004), "Simulation and optimization of aerodynamic stall control using a synthetic jet," *2nd AIAA Flow Control Conference*.

Duvigneau, R. and Visonneau, M. (2006), Optimization of a synthetic jet actuator for aerodynamic stall control, *Computers and Fluids*, Vol. 35, No. 6, pp. 624–638.

Englar, R and G. Huson, (1983), Development of advanced circulation control wing lift airfoils. *AIAA paper* 83-1847,.

Englar, R, M. Smith, M. Kelley, and R. Rover, (1993). Development of circulation control technology for application to advanced subsonic aircrafts. *AIAA paper* 93-0644.

Englar, R.J. (2005), Overview of circulation control pneumatic aerodynamics: Blown force and moment augmentation and modification as applied primarily to fixed wing aircraft, *Proceedings of the 2004 NASA/ONR Circulation Control Workshop*, NASA CP-2005-213509, pp23-66.

Englar, R.J., and Huson, G.G., (1983), Development of advanced circulation control wing high lift airfoils," *AIAA Paper* 83-1847,

Englar, R.J., Smith, M.J., Kelley, S.M., and Rover, R.C. III,(1993), Development of circulation control technology for application to advanced subsonic aircraft," *AIAA Aerospace Sciences Conference, AIAA Paper* No. 93-0644.

Englar, R.J., Smith, M.J., Kelley, S.M., and Rover, R.C. III, (1994),"Application of Circulation Control to Advanced Subsonic Transport Aircraft, Part I: Airfoil Development," *J. of Aircraft*, Vol. 31, No.5, pp. 1169–1177.

Englar, R.J., (2000), Circulation control pneumatic aerodynamics: Blown force and moment augmentation and modification; Past, present and the future, *AIAA Paper* 2000-2541.

Fiedler, H.E., and Fernholz, H.-H. (1990), On Management and Control of Turbulent Shear Flows, *Prog. Aerospace Sci*. 27, pp. 305-387.

Florescu D., Florescu I., Nedelcut F., Nedelcu I.(2010), Fuselage airstream simulation for a Coandă UAV", *Technical Sciences and Applied Mathematics*. pp. 83-88.

Frank A., McGrewy J.S., Valentiz M, Levinex D. and How, J.P. Hover, Transition, and level flight control design for a single-propeller indoor airplane. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi= 10.1.1.212.6553 and rep=rep1 and type=pdf, April 2015

Godard, G. and Stanislas, M., (2006), Control of a decelerating boundary layer. Part 1: Optimization of passive vortex generators. *Aerospace Science and Technology*, 10:181–191.

Gad-el-Hak, M.(1998), Introduction to Flow Control, in Flow Control: Fundamentals and Practices, *Springer-Verlag*, pp. 1-108.

Gad-El-Hak M., A. Polland, and J. Bonnet (1998), Flow Control: Fundamentals and Practices, *Springer*.

Gad-El-Hak M, (2007), Flow Control: Passive, Active, and Reactive Flow Management. *Cambridge University press*.

Grasmeyer, J. M. and Keennon, M. T. (2001), Development of the black widow micro air vehicle. *Progress in Astronautics and Aeronautics* 195: 519–535.

Green, W. and Oh, P. (2009): A hybrid MAV for ingress and egress of urban environments. *IEEE Transactions on Robotics* 25(2): 253–263.

Gu, W., Robinson, O. and Rockwell, D.(1993), "Control of Vortices on a Delta Wing by Leading-Edge Injection, *AIAA Journal*, vol. 31, no. 7, pp. 1177-1186.

Coandă H., Propelling Device, *US Patent Office, U.S. Patent* 2,108.652.(1938).

Harris M.J., (1981), Investigation Of The Circulation Control Wing -Upper Surface Blowing High-Lift System On A Low Aspect Ratio Semispan Model, *DTNSRDC-ASED*-81-10 May

Hatton, G., GFS Projects Ltd.(2007), Thrust vertical-take-off air vehicle with lift created by a rotary impeller causing air to flow over convex outer surface , *UK Patent Office* no. GB 2,452,255.

Helin, H.E. and Watry, C.W., 1994, Effects of Trailing-Edge Jet Entrainment on Delta Wing Vortices”, *AIAA Journal*, vol. 32, no. 4, pp. 802-804.

Henri-Marie Coandă, (1935), *Perfectionnementaux propulseurs*, *Brevet d’invention France*, no.796.843 /15.01.

Henri-Marie Coandă, (1934), *Procédé etdispositif pour faire dévier une veine defluide pénétrant dans un autre fluide*, *Brevet d’invention France*, no. 792.754/08.10.1934

Howard, R., and Kaminer, I.(1995), Survey of unmanned air vehicles, *In Proceedings of the American Control Conference*, pp. 2950-2953.

Hefner, J. and Bushnell, D. (1990), Viscous drag reduction in boundary layers, Progress in astronautics and aeronautics volume 123. *American institute of aeronautics and astronautics*.

Hefner, J., Weinstein, L. and Bushnell, D. (1979), Large-eddy break-up scheme for turbulent drag reduction. *In AIAA Prog. Astro. Aero*., volume 72, pages 447–463.

Jones G.S., Viken S.A., Washburn A.E., Jenkins L.N., Cagle C.M. (2002), An active flow circulation controlled flap concept for general aviation aircraft applications, *Flow Physics and Control Branch NASA Langley Research Centre*, AIAA2002-3157.

Jones, G.S.; Englar, R., (2003), Advances in Pneumatic-Controlled High-Lift Systems through Pulsed Blowing. *In Proceedings of AIAA 2003-3411 21st Applied Aerodynamics Conference*, Orlando, FL, USA, 23–26 June 2003; doi:10.2514/6.2003-3411.

Jones, K.; Bradshaw, C.; Papadopoulos, J. and Platzer, M. (2005): Bio-inspired design of flapping wing micro air vehicles. *Aeronautical Journal* 109(1098): 385–394.

Kweder J., Panther C.C., Smith J.E. (2011), Applications of circulation control, yesterday and today, *International Journal of Engineering*, (IJE) 195;4(5),pp. 411-429.

Lax, M., and Sutherland, B.(1996), An extended role for unmanned aerial vehicles in the royal Australian Air Force. *Tech. Rep*. Paper 46, Royal Australian Air Force, Air Power Studies Centre.

Liebeck, R.H., (1978), Design of subsonic airfoils for high lift, *Journal of Aircraft*, Vol. 15, No. 9, pp. 547-561.

Liu, Y., Sankar, L. N., Englar, R., and Ahuja, K., (2001), Numerical simulations of the steady and unsteady aerodynamic characteristics of a circulation control wing," *AIAA 2001-0704, 39th AIAA Aerospace Sciences Meeting*, Reno, NV

Loth, J.L., Fanucci, J.B., Roberts, S.C.,(1976), Flight Performance of a Circulation Controlled STOL Aircraft.” *Journal of Aircraft, American Institute of Aeronautics and Astronautics*, V13, No. 3,.

Walsh M. and Weinstein L. (1978), Drag and heat transfer on surfaces with small longitudinal fins. *AIAA paper* 78-1161.

Mamou M. and Khalid M. (2007), “Steady and unsteady flow simulation of a combined jet flap and Coandă jet effects on a 2D airfoil aerodynamic performance”, *Revue des Energies RenouvelablesCER’07 Oujda*: pp. 55–60.

McCormick, B. W., (1999), Aerodynamics of V/STOL Flight, *Dover Publications*,

McCormick, S. and Gursul, I.(1996), Effect of Shear Layer Control on Leading EdgeVortices, *Journal of Aircraft*, vol. 33, no. 6, pp. 1087-1093.

Miller, J., Minear, P., Niessner, A., DeLullo, A., Geiger, B., Long, L., and Horn, J., (2005), Intelligent unmanned aerial vehicle flight systems. *In Proceedings of the 2005 AIAA InfoTech@Aerospace Conference.*

Mirkov N. and Rasuo B.(2010), "Numerical simulation of air jet attachment to convex walls and applications", *Proceedings of 27th International Congress of the Aeronautical Sciences* - ICAS 2010, Nice, France.

Moin, P. and Bewley, T. (1994) "Feedback Control of Turbulence," *Appl. Mech. Rev*. 47, pp.S3-S13.

Mueller, T. J. and DeLaurier, J. D. (2001): An overview of micro air vehicle aerodynamics. Fixed and flapping wing aerodynamics for micro air vehicle applications, *Progress in Aeronautics and Astronautics, AIAA*, 249–272.

Nakata, T.; Liu, H.; Tanaka, Y.; Nishihashi, N.; Wang, X. and Sato, A. (2011): Aerodynamics of a bio-inspired flexible flapping-wing micro air vehicle. *Bioinspiration and Biomimetics* 6(4): 045 002

Naudin J.L., (2006), GFS UAV Project, Retrieved on 25.04.2010, from JLN Labs Online: http://jlnlabs.online.fr/gfsuav/gfsuavn0 1a.htm

Naudin, J. L. (2007), Available: http://jlnlabs.online.fr/gfsuav/gfsuavn01a.htm. Accessed June 2013.

Nedelcut, F. (2010), Towards a new class of aerial vehicles using the Coandă effect, Brasov. *In International Conference AFASES.*

Newman, B.G. (1961),The Deflexion of Plane Jets by Adjacent Boundaries Coandă Effect, Boundary Layer Flow Control, *Pergamon Press*, Vol. 1.

Nonami, K. (2007): Prospect and Recent Research and Development for Civil Use Autonomous Unmanned Aircraft , as UAV and MAV. *Journal of System Design and Dynamics* 1(2): 120–128.

Padfield, G., and Lawrence, B. (2003), The Birth of Flight Control: An Engineering Analysis of the Wright Brothers' 1902 Glider. *The Aeronautical Journal*, December (2003), 697-718.

Phillips, S., Lambert, C., and Gursul, I., (2003), Effect of a trailing-edge jet on fin buffeting, *Journal of Aircraft, vol. 40, no. 3, pp. 590-599.*

Roderick, W. E. B. (1961),"Use of the Coandă Effect for the Deflection of Jet Sheets Over Smoothly Curved Surfaces, Part 11, *University of Toronto, Institute of Aerophysics*, Technical Note No. 5.

Rose, T. Buttler, (2006), Secret Projects Flying Saucer Aircraft, *Midland Publishing Limited* ISBN 1857802330, 9781857802337, Leicester, UK.

Jee, S. Lopez O., Muse J., Calise A., and Moser R. (2008), Unsteady flow simulation of a controlled airfoil. In *Bulletin of the American Physical Society* - APS DFD 2008.

Saeed, G B Gratton,(2012), An approach to evaluate lift generated by an annular-Coandă-wing for vertical/short take-off and landing applications, *Proceedings of the Institution of Mechanical Engineers*, Part G: Journal of Aerospace Engineering, 226,10,pp.1298-1314.

Sarris, Z. (2001), Survey of UAV applications in civil markets. *The 9th IEEE Mediterranean Conference on Control and Automation*

Schroijen M., Van Tooren M. (2009), "MAV propulsion system using the Coandă effect, *American Institute of Aeronautics and Astronautics*, *AIAA/ASAME/SAE/ASEE, Exhibit*, USA: Denver Colorado, Joint Propulsion Conference, pp. 1-10.

Seifert, A., Darabi, A., and Wygnanski, I. (1996), Delay of airfoil stall by periodic excitation, *Journal of Aircraft*, Vol. 33, No. 4, pp. 691–698.

Sellers, William L. III, Singer, Bart A., and Leavitt, Laurence D.,(2003), Aerodynamics for revolutionary air vehicles, AIAA Paper 2003-3785, *21st Applied Aerodynamics Conference*, Orlando, FL.

Shaw, S. T., Hill, J. L., Qin, N. (2005), Application of engineering transition models to an isolated Helicopter rotor in hovering flight, *AIAA Paper* 2005-0467

Shih, C. and Ding, Z.,(1996), Trailing-edge jet control of leading-edge vortices of a delta wing, *AIAA Journal*, vol 34, no(7), , 1447-1457.

Shyy, W.; Berg, M. and Ljungqvist, D. (1999): Flapping and flexible wings for biological and micro air vehicles. *Progress in Aerospace Sciences* 35(5): 455–505.

Singh, B., Ramasamy, M., Chopra, I. and Leishman, J. (2005), Experimental studies on insect-based flapping wings for micro hovering air vehicles. *46th annual structural dynamics and materials conference* 2005, Austin, Texas 20742.

Tongchitpakdee, C. (2007), *Computational studies of the effects of active and passive circulation enhancement concepts on wind turbine performance*, Doctorate of Philosophy Dissertation, School of Aerospace Engineering, Georgia Institute of Technology.

Tongchitpakdee, C., Benjanirat, S., and Sankar, L.N. (2006), Numerical Studies of the Effects of Active and Passive Circulation Enhancement Concepts on Wind Turbine Performance," *Journal of Solar Energy Engineering*, Vol. 128.

Valeriu Dragan,(2013), Development of a laminar boundary layer model for curved wall jets, *INCASBULLETIN*, Volume **5,** Issue 2/ 2013, pp. 15 – 22, ISSN 2247–4528, ISSN 2066–8201.

Van Dam, C.P., Chow, R., Zayas, J.R., and Berg, D.E., (2007), Computational investigations of small deploying tabs and flaps for aerodynamic load control, *The Science of Making Torque from the Wind, Denmark, J. Phys.: Conf. Series*, Vol. 75, No.1.

Vermeulen C., P. Lejeune, J. Lisein, P. Sawadogo and P. Bouché. (2013), Unmanned aerial survey of elephants. *PLOS ONE 8.2*: e54700

Viieru, D., Tang, J., Lian, Y., Liu, H., and Shyy, W. (2006), Flapping and flexible wing aerodynamics of low Reynolds number flight vehicles, *In Proceedings of the 44th AIAA Aerospace Sciences Meeting and Exhibit.*

Wang, Z. and Gursul, I., (2005), Effects of jet/vortex interaction on delta wing aerodynamics, *1st International Conference on Innovation and Integration in Aerospace Sciences*, 4-5 August, Queen's University Belfast, UK.

Washburn, A. E., S. Althoff-Gorton, and S. G. Anders, (2002), Snapshot of active flow control research at NASA Langley, *AIAA Paper* 2002-3155, 1st Flow Control Conference, St. Louis, MO.

Wilson, III, S. B.,(2000), Micro air vehicles (MAV), *Presentation at the AIAA Student Chapter meeting at the University of Maryland*, College Park, Oct 19, 2000.

Winchester, Jim (2005), American Military Aircraft. Grange Books PLC. p. 68. ISBN 978-1-84013-753-8. Retrieved 25 March2015

Wood, N.J., Roberts, L. and Celik, Z.(1990), Control of asymmetric vertical flows over delta wings at high Angles of attack", *Journal of Aircraft,* vol. 27, no. 5,pp. 429-435.

Wood, N.J., Roberts, L. and Celik, Z.,(1990) "Control of Asymmetric vertical flows over Delta Wings at High Angles of Attack", *Journal of Aircraft*, vol. 27, no. 5, pp. 429-435.

Yang, L.J. (2012), The micro-air-vehicle golden snitch and its figure-of-8 flapping. *Journal of Applied Science and Engineering* 15(3).

Yenne, B.(2004), Attack of the Drones: a History of Unmanned Aerial Combat. Zenith Press, Minneapolis, MN, USA

Zha G.-C and D. C. Paxton, (2006), A novel flow control method for airfoil performance enhancement using co-flow jet. *Applications of Circulation Control Technologies*, Chapter 10, p. 293-314, Vol. 214, *Progress in Astronautics and Aeronautics*, AIAA Book Series, Editors: Joslin, R. D. and Jones, G.S.

Zha G.-C, C. Paxton, A. Conley, A. Wells, and B. Carroll, (2006), Effect of injection slot size on high performance co-flow jet airfoil," *AIAA Journal of Aircraft*, vol. 43.

Zha G.-C, B. Carroll, C. Paxton, A. Conley, and A. Wells,(2007), High performance airfoil with co-flow jet flow control," *AIAA Journal*, vol. 45.

Zha G.-C., W. Gao, and C. Paxton,(2007) "Jet effects on co-flow jet airfoil performance, *AIAA Journal*, No. 6,, vol. 45, pp. 1222–1231.