Progress and Development of Coandă Jet and Vortex Cell for Aerodynamic Surface Circulation Control – An Overview

Harijono Djojodihardjo*

*Department of Aerospace Engineering, Universiti Putra Malaysia, Selangor, MALAYSIA. E-Mail: harijono@djojodihardjo.com

***Abstract*—**Coandă jet 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, along with continuous, synthetic and pulsed jets, compliant surface, vortex-cell, and the like. Coandă jet has also been applied in the development of novel aircrafts for short take off, while another circulation enhancement technique known as Trapped Vortex Cavity (TVC) is currently being given significant considerations. It is with such motivation that within the aerodynamics surface blowing techniques, Coandă jet and vortex-cell will be reviewed, to assess their characteristics in dramatically alter the behavior of aerodynamic components such as airfoils, wings, and bodies. Capitalizing on a host of research and technology development efforts on Coandă and surface blowing circulation enhancement, the present work reviews the influence, effectiveness and configuration of airfoil surface blowing of Coandă-jet and Trapped Vortex Cavity in circulation enhancement and control of aerodynamic surfaces. The crux of the TVC active research is their stabilization, while Coandă enhanced lift enhancement technique has, to a certain extent reached a stage that it can be easily implemented with advantage.

***Keywords*—**Aerodynamic Surface Blowing; Coandă Effect; Circulation Control; Lift Augmentation; Trapped Vortex Cell.

***Abbreviations*—**Blended-Wing-Body (BWB); Circulation Control (CC); Circulation Control Wing (CCW); Coandă Configured(CC); Computational Fluid Dynamics (CFD); Cruise Efficient Short Take Off and Landing (CESTOL); Extreme Short Take-off and Landing (ESTOL); Horizontal Axis Wind Turbine (HAWT); Jet Momentum Coefficient (C_μ); Lift Coefficient (C_L); Lift over Drag Ratio (L/D); Micro-Air Vehicle (MAV); National Aeronautics and Space Administration (NASA); No-Tail-Rotor (NOTAR); Pressure Coefficient (C_p); Reynolds-averaged Navier-Stokes (RANS); Short/Vertical Take-Off and Landing (S/VTOL); Trailing Edge (TE); Trapped Vortex Cavity (TVC); Vertical Axis Wind Turbine (VAWT); Vertical Take-Off and Landing (VTOL).

I. INTRODUCTION

GAD-el Haq (2007) stipulated that the science of flow control can be traced back to Prandtl (1904), who made a breakthrough in the science of fluid mechanics by introducing the boundary-layer theory and elucidated the physics of the separation phenomena and the control of the boundary layers. Gad-el Haq (2007) utilization of this scientific method for flow tailoring can be regarded as marking the birth of the second era of flow control. The utilization of flow control has noticeably increased in the last decades due to the growth of aircraft and propulsion technologies [Harris, 1981; Englar et al., 1994, 2012; Gad-el-Hak, 1996; Liu et al., 2001; Liu, 2003; Shojaefard et al., 2005; Mamou & Khalid, 2007; Radespiel et al., 2009; Min et al, 2009]. These active control techniques can appreciably improve the performance of many aerodynamic components such as airfoils, wings, and bodies. Since the wing areas are sized by the takeoff and landing conditions, the wing may have approximately twice as large as required for efficient cruise [Moore, 2005], as well as lower wing loading which is much more susceptible to turbulence, thus reducing the cruise efficiencies of Transport Aircrafts. Various methods for enhancing aerodynamic surface control and wing circulation enhancement have consequently been introduced. These circulation enhancement methods can be classified as summarized in figure 1, adapted from Radespiel et al., (2009) and Werner-Spatz et al., (2012).

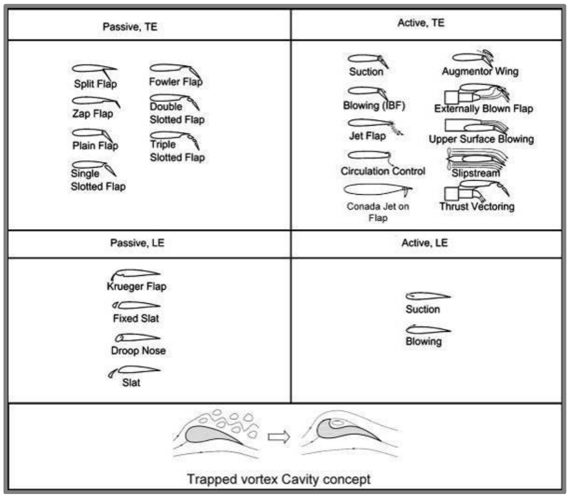


Figure 1: Various Types of Active and Passive Method for Controlling Aerodynamic Surface Circulation (Extended from Werner-Spatz et al., (2012))

Kweder et al., (2011) noted that four main benefits have been achieved by using an active circulation control method on fixed wing aircraft for aerodynamic moment enhancement. Circulation control requires very small movement, or even non-moving, control surfaces. Lift augmentation can be achieved independent of the airfoil angle-of-attack, and the jet turning angle is not limited by physical jet exit angle nor flap deflection angle. In addition, the jet blowing momentum is very effective in producing high aerodynamic force augmentation. These benefits make circulation control by surface blowing more widely potential. Circulation control is a viable active flow control approach that has been considered to meet the NASA Subsonic Fixed Wing project's Cruise Efficient Short Take Off and Landing goals [Jones et al, 2008]. Recent interest in Circulation Control (CC) technology has been prompted by the National Aeronautic and Space Administration (NASA) Cruise Efficient Short Take Off and Landing (CESTOL) initiative and the Air Force Research Laboratory (AFRL) Advanced Joint Air Combat System program. Circulation Control (CC) technology initiatives highlight the necessity for enhanced high-lift systems to meet take-off and landing objectives that are incorporated into transonic cruise configurations. Consequently there is a need to optimize the entire wing and propulsion system with particular attention on aerodynamic system efficiency, engine out condition safety, and large aerodynamic moments control issues.

It should be noted, however, that another perspective can be considered from the point of view of synthetic jets, which has been comprehensively discussed by Glezer (2011). Out of these aerodynamic surface circulation control methods and to have comparative assessment of circulation control techniques, two novel and strategic systems will be discussed, these are Coandă jet and trapped vortex cell.With the progress of modern airplanes of larger dimensions and innovative configurations such as Blended-Wing-Body (BWB) airplanes, and modern fighters with higher maneuverability and agility, thick wings have been conceived to be beneficial. To overcome the drawback of thick airfoils due to the high value of their drag coefficient and early flow separation phenomenon, even for small incidence angles, the use of intense trapped vortex cavity to force the potentially separated flow to remain attached has been given serious considerations, such as in the "Vortex Cell 2050" (2005), a European funded research project launched at the end of 2005. The effort is focused on the possibility to control the flow separation using trapped vortex cavities equipped with a suction system aimed to stabilize the vortex. Following the work of the author and colleagues [Hamid et al., 2010; Djojodihardjo et al., 2010; 2011; 2013], the present work reviews the applications of Coandă jet within the framework of aerodynamic surface circulation control, and to identify key principles and various techniques that have been applied to take advantage of Coandă-jet for aerodynamic performance enhancement for aircrafts and wind-turbines. With due considerations to other flow control methods, the advances in trapped vortex cavity technologies are discussed in analyzing the benefits of these two technologies for various applications.

II. CIRCULATION CONTROL

The large rounded Trailing Edge (TE) on the early Circulation Control Wing (CCW) designs give rise to high drag penalty in case the jet is turned off. Tongchitpakdee (2007) countered that issue by designing the airfoil TE lower surface as a flat surface, while keeping the upper surface highly curved to produce a large jet turning angle, leading to high lift. The forward rotation of the lift vector contributes to the generation of power from wind turbines, and any increase in the magnitude of the lift force (while keeping drag small, and L/D high) will immediately contribute to a corresponding increase in induced thrust and torque [Tongchitpakdee et al., 2006]. If there is some power consumed in the generation of the jet, there should be a net positive increase in power generated for this concept to be attractive and potential for increasing wind turbines power generation. Although a crude estimate can readily be made to take into account the power consumed in generating the Coandă-jet, the present study only addresses the aerodynamic aspects of this problem. Circulation Control Wing (CCW) technology for increasing the bound circulation and hence the sectional lift coefficient of the airfoil has been extensively investigated both experimentally and numerically over many years. One of the well-known techniques in implementing circulation control is by tangentially blowing a small high velocity jet over a highly curved surface, in particular over a rounded TE, which will produce early flow separation otherwise. Using such technique, the boundary layer and the jet sheet will remain attached along the curved surface due to what is known as the Coandă effect thus causing the jet to turn without separation. Consequently, the rear stagnation point will move rearward toward the lower airfoil surface. This flow change will then produce an additional increase in circulation around the entire airfoil. Looking into the outer irrotational flow, through the action of the boundary layer, the outer flow will also turned accordingly, producing higher value of lift coefficient comparable to that achieved from conventional high lift systems. Tongchitpakdee et al., (2006) and Tongchitpakdee (2007) observed that early Circulation Controlled Wing designs typically had a large-radius rounded TE to maximize the lift benefit. However, such favorable effect will be accompanied by higher drag penalty when the Coandă jet is not activated. Tongchitpakdee (2007) also pointed out that to reduce such penalty one can make the lower surface of the airfoil TE a flat surface, while maintaining the upper surface in the vicinity of the TE highly curved, since such geometry will produce a large Coandă jet turning angle, hence higher lift. Circulation control technology to produce large values of lift advantageous for wind turbine design while keeping drag small (and L/D high) will immediately contribute to a corresponding increase in induced thrust and torque. Numerical simulation carried out by Tongchitpakdee (2007) looked into two approaches of introducing Coandă-jet, i.e., at the leading edge and at the trailing edge, both at the appropriately chosen locations. A leading edge blowing jet was found to be helpful in increasing power generation at leading edge separation cases, while a TE blowing jet otherwise.

III. BASIC PRINCIPLES AND ANALYSIS

As a basis for airfoil surface blowing, one may start with trailing edge blowing. The trailing edge jet can be directed downward as a "jet-flap" which has been the subject of a great deal of analysis. For further references, the well known Kutta-Joukowski is re-derived to apply to these cases. Consider the situation of a self-propelled, 2-D wing in a uniform, steady flow as depicted in figure 2 (adapted from Keen (2004)), ignoring body forces and assuming design condition. Using first principles, the force on this body is given by (Karamcheti, 1966)):

$$\mathbf{F} = -\int_C pndc - \dot{m}_p \left(u_j - U_\infty\right)\mathbf{i} \qquad (1)$$

where p is the pressure, dc is a differential length along a control surface, and m_p is the mass flow rate per unit span. Knowing the value on the integral over the far-field control surface, the value of the integral over any surface enclosing the body will also be known, including one which is right on the body surface. The force expression can be written as [Djojodihardjo et al., 2013]:

$$\mathbf{F} = -\mu_\infty U_\infty \times \int_C \left(\mathbf{n}\times\mathbf{q}\right)dc - \dot{m}_p \left(u_j - U_\infty\right)\mathbf{i} \qquad (2)$$

where q is the difference between the total fluid velocity at a point and the free stream value. It can be shown [Keen, 2004] that the total force on the body can then be written as:

$$\mathbf{F} = \rho_\infty U_\infty \Gamma_{\text{mod}}\mathbf{k} + \rho_\infty U_\infty \left(u_j y \sin\delta\right)\mathbf{k} - \dot{m}_p \left(u_j - U_\infty\right)\mathbf{i} \qquad (3)$$

This relationship is the modified Kutta-Joukowski theorem for an airfoil with additional blowing. The addition of surface blowing at the trailing edge modifies the original (or baseline) circulation, and due to the nature of the resulting jet, produces a net thrust. To justify the results of Coandă-jet study, and to give a physical explanation of the effect of Coandă-jet, one may attempt to carry out simple calculation using similar first principle and Kutta-Joukowski law for potential flow. Using Kutta-Joukowski law and considering Coandă-jet contribution to the lift, Djojodihardjo et al., (2011, 2013) arrive at the formula:

$$\mathbf{F} = \left\lfloor \rho_\infty U_\infty \Gamma_{original} + \rho V_\infty \left(V_{Coanda-jet} h_{Coanda-jet}\right)\right\rfloor \mathbf{k} \qquad (4)$$

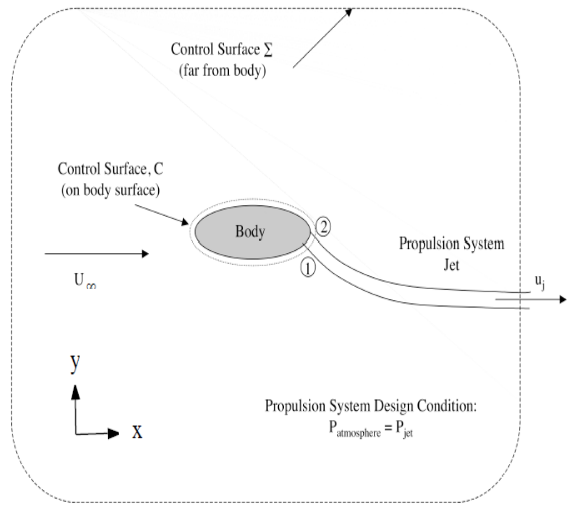


Figure 2: Sketch of Blown Section and Control Surfaces [Keen, 2004]

where $h_{Coanda-jet}$ is the moment arm of the Coandă-jet with respect to the airfoil aerodynamic center. Γ is now the total modified circulation of the wing-surface blowing system, and the second term describes the reaction lift due to the jet. In the above equation, δ denotes the width of the jet. Circulation Control Wing (CCW) technology is known to be beneficial in increasing the bound circulation and hence the sectional lift coefficient of airfoil. Circulation control is implemented by tangentially blowing a small high-velocity jet over a highly curved surface, such as a rounded trailing edge. This causes the boundary layer and the jet sheet to 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. The rear stagnation point location moves toward the lower airfoil surface, producing additional increase in circulation around the entire airfoil. The outer irrotational flow is also turned substantially, leading to high value of lift coefficient comparable to that achievable from conventional high lift systems. These techniques are depicted in figures 3 and 4, illustrating trailing edge and leading edge blowing, respectively. The ability of circulation control technology to produce large values of lift is also advantageous for wind turbine design since any increase in the magnitude of the lift force (while keeping drag small, and L/D high) will immediately contribute to a corresponding increase in induced thrust and torque. Harris (1981) also proved that the 96 degrees arc corner at the trailing edge produces more deflection than corners with the same radius and with a greater arc length at higher jet thrusts at the same Coandă jet momentum.

IV. Review of Coandă Technique Development for Applications

4.1. Historical Development

In the early 1900's, Coandă (1934) and Coandă & France (1936) conducted experiments with unusual mounted engine in front of an aircraft, and discovered a strange phenomenon that the hot airflow from the engine nozzle attracted to nearby surfaces (aircraft fuselage). This Coandă engine was an experimental plane powered by a ducted fan. For this discovery and patent, Coandă referred it as "Method and apparatus for the deviation of a fluid into another fluid". This invention was further discussed by the leading aerodynamicist during that time, Theodore von Karman named it as Coandă effect. Sometimes in 1920's, another inventor, Willard Custer, took shelter in a barn during a hurricane, when suddenly, the roof of the barn was blown away ("lifted-off") and soared through the air. This event led him to realize, that what happened was due to the notion that the pressure forces acting on the upper surface of the barn roof was much lower than the lower surface, just like an aircraft wing. He construed that the lift is "due to the speed of air, not the airspeed" [Liska, 1957a; Liska, 1957b]. Custer's novel design of the aircraft features a half circular wing aircraft to place the propeller so that the upper surface of that part of the wing can take advantage of the speed of air from the propeller, as shown in figure 5, exhibiting such principle.

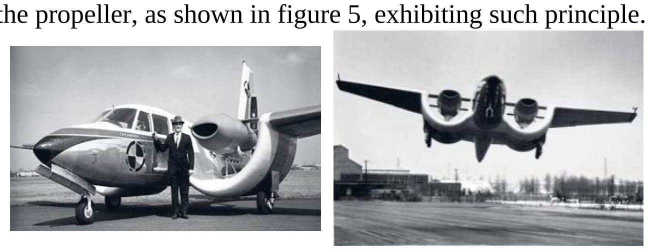


Figure 5: Custer Channel-Wing Anonymous, Aircraft [Liska, 1957; Englar & Campbell, 2002]

4.2. Combined Blowing Circulation Control Application to Extreme Short Take-Off and Landing Vehicles

De la Montanya et al., (2007) carried out research using the Coandă effect to shorten Landing and Take-off of airplanes, in the framework of NASA Ames research Center search for Extreme Short Take-off and Landing (ESTOL) vehicles to reduce the airplanes take-off and landing length. In this regards, a jet is tangentially blown from a slot near the airfoil trailing edge. In the initial stage, de la Montanya et al., (2007) examined two dimensional flows to better understand the blowing effect. In this regard, they obtain larger overall lift when the blowing coefficient is increased. In next the step, they collected lift and drag data in three dimensional flow. Four flap deflections (0, 30, 60, and 90) and different blowing coefficients were tested. Their research arrived at some favorable configurations to meet their objectives. For an angle of flap deflection of 30^{o} and blowing coefficient of 0.35 the shortest take-off distance of 2400ft was achieved. The shortest landing distance was 2000 at an angle of flap deflection of 90^{o} and blowing coefficient of 0.34. Also the lift coefficient gained was up to 3.5. De la Montanya et al., (2007) compare lift coefficient C_L versus Coandă -jet momentum coefficient Cμ with earlier Harvell & Franke (1985) CFD studies; the comparison, as exhibited in figure 6, showed excellent agreement, although there was a little difference in the jet slot place and shape of the airfoils. De la Montanya et al., (2007) utilizes various values of airfoil x/c and h/c, namely 89.86% and 0.0016 and for GTRI case the corresponding values were x/c = 88.75% and h/c = 0.0019, respectively.

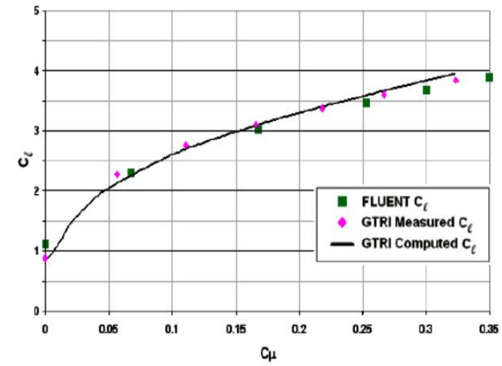


Figure 6: Lift Coefficient CL Versus Coandă–Jet Momentum Coefficient Cμ ; Comparison between De la Montanya et al's (2007) and Harvell & Franke (1985) Data

Nishino et al., (2010) and Rumsey & Nishino (2011) carried out a numerical study over a nominally two-dimensional circulation control airfoil using a Large Eddy Simulation (LES) code and two Reynolds-averaged Navier-Stokes (RANS) codes, comparing both approaches on a circulation control airfoil. Different Coandă jet blowing conditions are investigated, as well as the influence of grid density, and using incompressible and compressible flow solvers. The incompressible equations are found to yield negligible differences from the compressible equations up to at least a jet exit Mach number of 0.64. The effects of different turbulence models are also studied. Models that do not account for streamline curvature effects tend to produce jet separation from the Coandă surface too late. Naqvi (2006) performed computational approach using Navier Stokes Equations (Computational Fluid Dynamics) DSS2, a two dimensional RANS code developed by Professor Lakshmi Sankar of Georgia Institute of Technology for analysing circulation control airfoil characteristics associated with NASA proposed Super Short Takeo® and Landing and Extremely Short Take-off and Landing (ESTOL) Aircraft. The prediction capability produced this research effort can be integrated with the current conceptual aircraft modelling and simulation framework. The Circulation Control relies on the tendency of an emanating wall jet to independently control the circulation and lift on an airfoil. Since circulation control airfoils utilizes a round trailing edge, the rear stagnation point is free to move, and the location of rear stagnation point is controlled by the blown jet momentum. This provides a secondary control in the form of jet momentum with which the lift generated can be controlled. Trade-off analysis has been performed for baseline Super STOL configurations, and a thick supercritical airfoil modified for circulation control has been suggested performs adequately in extracting the benefits of circulation control during take-off and landing and at the same time producing reasonable values of L/D during cruise.

Three-dimensional CC blowing simulations have been carried out by Liu (2003) by investigating two cases. The first is a stream-wise tangential blowing on a wing-flap configuration, which demonstrated that a gradually varied CC blowing can totally eliminate the flap-edge vortex, thus reducing the flap-edge noise. The second case involves span-wise tangential blowing over a rectangular wing with a rounded wing tip. Although CC blowing can not totally cancel or eliminate the tip vortex, it can control and modify the location of the tip vortex, and increase the vertical clearance between the wing and the tip vortex, thus reducing the blade vortex interaction and the resulting noise.

V. Brief Review of Trapped Vortex Cavity Technologies

Trapping vortices is a technology for vortex shedding prevention and drag reduction in flows past bluff bodies, as well as maintenance of lift for flows past streamlined bodies at high angles of attack. The European VortexCell2050 program, for example, has the objective of delivering a new technological platform by combining two cutting-edge technologies, the trapped-vortex cell (TVC) and the active flow control [Vortex Cell 2050, 2005].

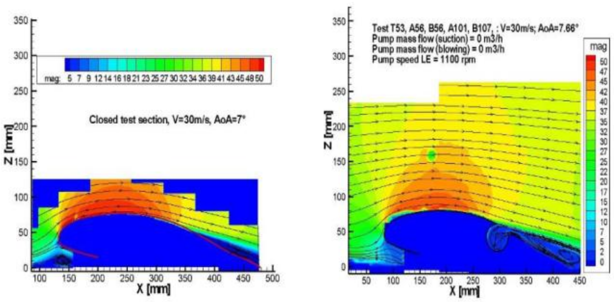


Figure 7: Flow Field without Suction in front the Model (Left) and with Suction (Right) [De Gregorio & Fraioli, 2008]

The interest of such new flow control and aerodynamic surface performance enhancement is illustrated by a series of continuing and recent research efforts, such as the pioneering work of Rossiter (1966) and Gharib & Roshko (1987), to mention only a few examples. Large vortices created in high-speed flows past bluff bodies are shed downstream, and produce an unsteady wake. These vortices and associated unsteady wake give rise to an increase in drag and unsteady loads on the body. Figure 7, which is reproduced from De Gregorio & Fraioli (2008), could give some insight into the potential of trapped vortex cavity in aerodynamic performance enhancement and its application for flow control on a high thickness airfoil. The influence of the TVC on the model without mass transfer has been investigated for different Wind-Tunnel speed (from 15 to 30 m/s) and different angle of attack. The flow field and pressure coefficient for all these cases indicated that the flow separates from the cavity tip and do not reattach downstream the cavity. This effect is more noticeable as the wind speed or the angle of attack is increased. Therefore lower velocities (such as 15 m/s) has been given more attention.

Looking from another perspective, synthetic jets can be introduced by the advection and interactions of trains of discrete vortical structures and have zero net mass flux. A distinctive feature of synthetic jets is that they are formed by intermittent suction between successive ejections through an orifice in the flow boundary, therefore introducing trains of discrete vortical structures that originate entirely from the fluid of the surrounding flow system, and thus transfer momentum to the cross flow without net mass injection across the flow boundary. Such jet can be produced by actuators integrated in the boundary of a cross flow, such as by the motion of a diaphragm that is built into one of the walls of an otherwise sealed cavity below the surface. However, when the actuation frequency is sufficiently high to be decoupled from global instabilities of the base flow, changes in the aerodynamic forces are attained by controlling the generation and regulation of ‘trapped’ vorticity concentrations close to the surface to modify its aerodynamic shape [Glezer, 2011].

A trapped vortex can manifest itself as a steady separation eddy above an aerofoil at high angle of attack. However, with the use of an appropriate cavity, a Trapped Vortex Cell (TVC) will be produced and a dramatic change in aerodynamic performance will take place. Practical utilization of the trapped-vortex idea poses a challenge, since the trapped vortex should be almost steady and remain in the close vicinity of the body. Therefore, the stabilisation of a trapped vortex has been considered as a major challenge in the European Vortex Cell 2050 project (2005). The influence of the TVC on the model without mass transfer has been investigated by many researchers, such as by Gregorio & Fraioli (2008) and Donelli et al., (2008a; 2008b; 2010). For the flow field and the pressure coefficient considered in the Wind-Tunnel investigation by De Gregorio & Fraioli (2008), the flow separates from the cavity tip and does not reattach downstream the cavity. This effect is more noticeable as the wind speed and/ or the angle of attack of the airfoil is increased. Figure 8, reproduced from De Gregorio & Fraioli (2008), shows the prevailing flow field pattern inside the cavity and immediately downstream the airfoil surface for a wind speed of 15 m/s and for six different values of angles of attack α (A, α=5.66° and F, α=12.66°). The figure reveals the magnitude of the flow stream lines and shows that for the smaller angle (α=5.66°) a weak vortical structure inside the cavity results, with its center located far from the geometrical center of the cavity and moved toward the shear layer region. Furthermore, the vortex is elongated toward the exit of the cavity. The vortex strength is not sufficiently large to force a flow reattachment. As the angle of attack α increases, the center of the vortex moves in the direction of the shear layer region and it is drawn outside the cavity, which in turn inducing further vortex shedding. At the same time, the fluid at the separated region downstream from the cavity is drawn inside the cavity.

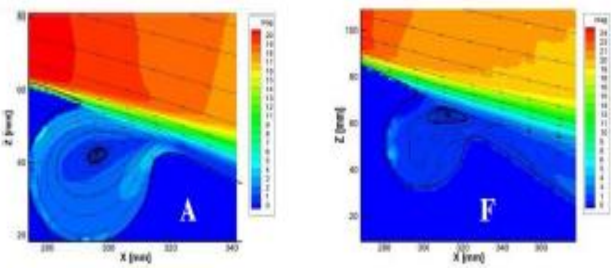


Figure 8: Flow Field Velocity inside the Cavity without Suction/Blowing Mass Flow [De Gregorio & Fraioli, 2008]

De Gregorio & Fraioli (2008) placed the pressure taps in the cavity between 54% and 66% of the model chord. The C_p values show that the typical pressure exhibits a clear expansion on the upper leading edge region up to a maximum value until the cavity region. At this point, i.e. in the cavity, the C_P value forms a plateau, and the flow is separated and unsteady. Further downstream from the cavity, the pressure continues to remain constant; this indicates that the flow is fully separated. At this relatively low velocity and low angle of attack of 5.66° and 6.66°, it is possible to characterize the typical pattern of the trapped vortex inside the cavity.Passive control has been investigated by Donelli et al., (2008) to examine the behavior of the TVC without any mass flow suction. The results showed that without any mass flow suction the TVC did not induce flow reattachment due to vortex shedding. Massive steady suction, however, induces flow reattachment due to the stabilization of an intense vortex in the cavity. Donelli et al., (2008a, 2008b, 2010) observed that by increasing the mass flow rate, the recovery-pressure increases and when a mass flow suction rate of 25.8 m^3/his applied, the flow is attached up to a 95% of the chord. The vortex is steadily located in the center of the cavity and the resulting flow is fully attached. From their research, De Gregorio & Fraioli (2008) concluded that passive TVC flow regulation is not able to control the flow separation. The vortex will not be restricted in the cavity and in addition there occurs vortex shedding which decreases the aerodynamic performance of the airfoil without TVC. However, active TVC flow control is able to govern the flow separation; full reattachment has been achieved for limited values of the blowing coefficient. The above brief review serves to illustrate the major challenge in developing trapped vortex cavity by a combination of trapped-vortex technology with active flow control. Associated with such concern, the European Vortex Cell 2050 (2005) project has formulated specific major objectives, among others, to develop a software tool for designing a thick airfoil with a trapped vortex assuming that the flow is stable, apart from small-scale turbulence, and to develop a methodology and software tools for designing a system of stabilization of such a flow.

VI. Selected Results from Recent Coandă Research

6.1. Recent Research Results as Proof of Concept

A study has been performed by Hall et al., (2006), to investigate the effect of Coandă-jet blowing on the upper or lower duct surface of a natural blockage turbofan thrust reverser. The Coandă-jet blowing on the lower duct surface (blocker) increases axial reverse thrust force and prevents separation. While, Coandă-jet blowing on the inlet ramp has a detrimental effect on the reverse thrust force generated. Sellars et al., (2002), has successfully carried out a joint experimental and a CFD investigation of circulation control, on a sharp leading edge delta wing configuration with two leading edge sweeps using Coandă blows over a semi-circular TE and shows that Coandă blowing circulation control on a delta wing can produce a significant lift increment. Later, Frith & Wood (2004) performed an experimental investigation on a full span delta wing test configuration in a closed-loop wind tunnel at 25m/s to investigate the concept of applying Circulation Control (CC) as a means of trimming an aircraft. It was found that only low values of momentum jet coefficient, C_μ up to 0.002, would be required to trim the aircraft at the range of angle of attack investigated. The variation of pitching moment about the quarter-chord indicates that circulation control could be used to trim an aircraft, as well as providing high lift. Moreover, the differential blowing could provide roll control, as the roll increment seemed to vary reasonably linearly with momentum jet. The Coandă propulsion concept is intended to fill the efficiency gap between the rotary wing and fixed wing Micro Aerial Vehicles (MAV), studied by Schroijen & van Tooren (2009). It should have the capability to hover efficiently as well as cruise efficiently. 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. The preliminary wind tunnel test and Euler computation showed a difference in the pressure coefficient of a factor of 2, which is probably caused by viscous effects, like boundary layer formation and separation [Schroijen & van Tooren, 2009]. Schroijen & van Tooren (2009) design was based upon an annular wing wrapped around a centrifugal flow generator, potentially creating a vehicle with no external moving parts, reduced vehicle aerodynamic losses compared to previous V/STOL technologies and substantially eliminating induced drag. It appears to offer greater potential at a micro-aerial vehicle scale with regard to fundamental “lift to weight ratio” performance parameter and shows that such a wing works best with a thick airfoil section. He also experienced efficiency losses on his design, mainly occurring from annular flow expansion and the problem on choosing the best blower slot heights. The modified approach was further explored and proved viable with the used of pure upper surface blowing with Coandă effect. Saeed & Gratton (2010) has conducted a research program in exploring a new lift system for Vertical/Short Take-off and Landing (V/STOL) aircraft to set a path for further research in the design of future V/STOL aircraft. Using a Coandă surface at the duct trailing edge, in his study on Ducted Fan Aerodynamics and Modeling, Ohanian (2011) demonstrated that by turning of the stream-tube exiting the duct, a normal force is created and a decrease in pitching moment results. At the leading edge,steady and synthetic jet blowing caused separation on the duct lip at highangles of attack. This separation reduced thrust and also decreases the nose-uppitching moment.Numerical simulation carried out by Tongchitpakdee (2007) looked into two approaches of introducing Coandă jet, i.e., at the appropriately chosen point in the vicinity of the trailing as well as leading edge. A leading edge blowing jet was found to be helpful in increasing power generation at high wind speeds. The progress of high speed computers exemplified by the availability of new generations of notebooks has made possible the use of first-principles-based computational approaches for the aerodynamic modeling of wind turbine blades, to name an example. These approaches are comprehensively based on the fundamental laws of conservation of mass, momentum, and energy, and hence they should be able to capture much of the physics in great detail. Such approaches should also be particularly helpful at high wind speeds, where appreciable regions of separation are present and the flow is unsteady. With such background Djojodihardjo & Hamid work [Hamid, 2010, Djojodihardjo et al, 2011; 2013] searches for favorable Coandă -jet lift enhanced configuration for wind turbine designs. For this purpose, after a rigorous review of Coandă-jet circulation control airfoil, a generic proof of concept approach in two-dimensional subsonic flow is performed. Numerical simulation using commercially available Navier-Stokes CFD method is carried out and a critical scrutiny of the computational procedure and grid generation is performed. Tongchitpakdee (2007) found that best lift enhancing effect could be facilitated by designing the lower part of the trailing edge surface to be flat and this finding is also incorporated in the present numerical investigation. Harris (1981) also proved that the 96 degrees arc corner at the trailing edge produces more deflection than corners with the same radius a greater arc length at higher jet thrusts with the same Coandă jet momentum.

The case studies performed here use normalized dimension: airfoil chord length of 1m and free-stream velocity of 10 m/sec. These correspond to Reynolds number in the order of 10^6, which is considered to be a typical situation. A simple two-dimensional CFD modeling using k-e turbulence model is utilized to reveal the key elements that could exhibit the desired performance criteria for a comprehensive series of configurations. Parametric study performed indicates that Coandă configured airfoil can only be effective in certain range of trailing edge radius, Coandă-jet thickness and momentum jet size; the location of the Coandă-jet was found to be effective when it is placed close to the trailing edge. The results are compared with existing experimental data for benchmarking. Three dimensional configurations are synthesized using certain acceptable assumptions.

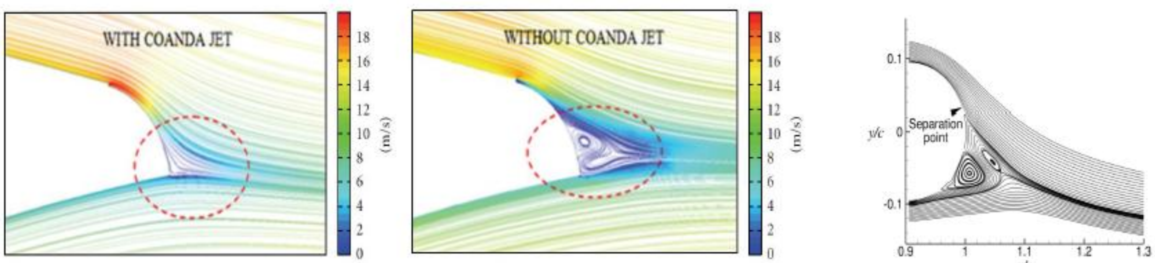


Figure 9: Velocity Fields of S809 Airfoil (a) with and (b) without Coandă-jet [Djojodihardjo et al., 2013] (c) observation of Nishino et al., (2010)

A trade-off study on the S809 Coandă configured airfoil is needed to judge the optimum configuration of Coandă-jet fitted Wind-Turbine design [Djojodihardjo et al., 2013]. CFD numerical computations for the flow-field around two-dimensional airfoil S809 has been carried out with the objective to study the extent to which the introduction of Coandă-jet enhance the aerodynamic performance of the airfoil, here represented by the L/D value, and lead to the following observations. The flow field in the vicinity of the TE for both configurations is shown in figures 9(a) and 9(b). figure 9(c), reproduced from Nishino et al., (2010) is also shown for verification purposes. Careful inspection of these figures may lead to the identification of the geometry of the flow that could contribute to increased lift, in similar fashion as that contributed by flap, jet flap, or Gurney flap. Figure 9(b) typifies the flow field around Coandă configured S809 airfoil without Coandă-jet (only with its back-step configuration), which is used here to get insight to the action of the Coandă-jet.

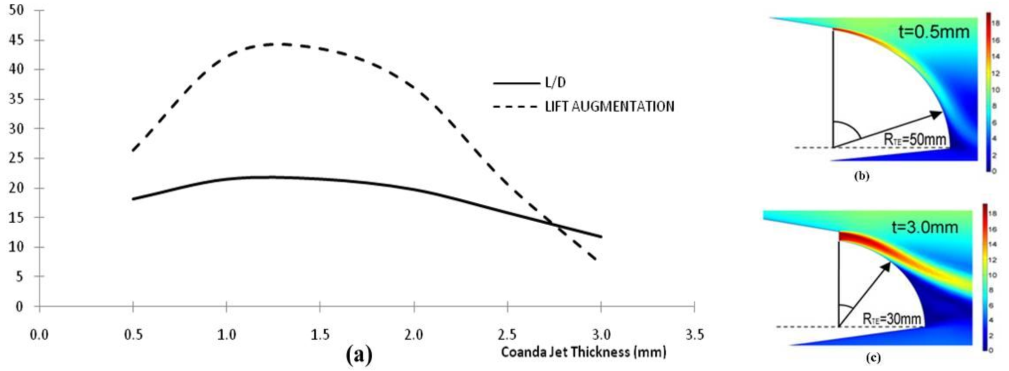


Figure 10: (a) The effect of jet thickness on the L/D and Lift Augmentation (Re = 1 x 106, RTE = 30 mm); (b) Flow Separation with t = 0.5 mm; (c) Flow Separation with t = 3.0 mm [Djojodihardjo et al., 2013]

To a certain extent, smaller TE radius produced better L/D than larger ones. It is also noted that after certain value, further increase in TE radius does not give significant lift augmentation, as indicated by figure 10. Their results also exhibit the effect of Coandă- jet location on the L/D and lift augmentation for various values of Momentum coefficient C_μ, as exhibited in figure 11.There is a range of effective Coandă-jet size designs, depending on their thickness.

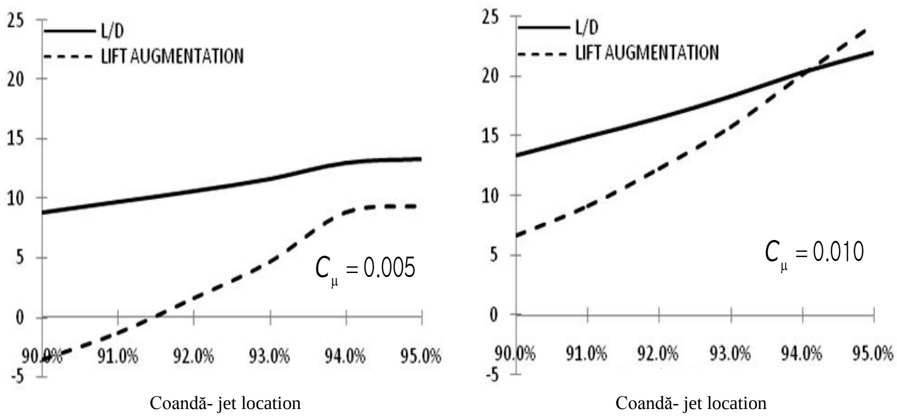


Figure 11: The Effect of Coandă-jet Location on the L/D and Lift Augmentation (Re = 1 × 106, RTE = 10 mm, t_{jet} = 1 mm); (a) C_μ=0.005; (b) C_μ=0.010; (Reproduced from Djojodihardjo et al., (2013))

Within the limits of local boundary layer thickness, there is a certain range of effective Coandă-jet thickness. The present study indicates that the optimum jet thickness is commensurate with the airfoil dimension. Care should be exercised to avoid flow separation at larger Coandă-jet thickness. With specific design specifications related to the Coandă-jet thickness and TE rounding-off size, the Coandă-jet momentum needed to improve the performance (lift augmentation due to jet) should not be excessive but sufficient to delay separation until the tip of the TE (where the upper surface meets the lower one). In addition, the Coandă-jet should be placed sufficiently close to the TE to avoid premature separation. With due considerations of prevailing three-dimensional effects, the two-dimensional numerical study can be used to direct further utilization of the CFD computational procedure for Wind-Turbine blade studies and their design optimization. Numerical results presented have been confined to zero angle-of-attack case, which has been considered to be very strategic in exhibiting the merit of Coandă-jet as lift enhancer.

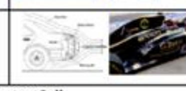
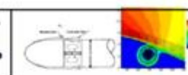
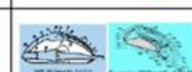
The numerical studies could be extended to higher angle-of-attack to obtain more comprehensive information, for which the choice of turbulence model will be more crucial. The study also shows that the maximum total energy output of Coandă configured airfoil may exceed that predicted by Betz limit [Djojodihardjo et al., 2013]. With all the results obtained thus far, it is felt that the present work is by no means exhaustive. Other issues may still be explored, such as how could the ambient air energy input that can be drawn by the Coandă-jet configured Wind-turbine either from the nacelle or elsewhere be utilized to energize the Coandă-jet, and for that matter, to lower the cut-in speed of Horizontal Axis Wind Turbine (HAWT) or the starting speed of Vertical Axis Wind Turbine (VAWT).

At this point, one could mention new initiatives to utilize Coandă effect for propulsion [Schroijen & van Tooren, 2009]. In this conjunction the work of Ragab et al., (2008) is of great interest.In their work, a numerical study of 3D circulation control (CC) using Coandă effect was carried out on a low aspect ratio wing of circular planform. The Reynolds-Averaged Navier-Stokes (RANS) equations and a second-order closure model for the Reynolds stresses are solved using commercial software (FLUENT6.3). The flow field around the wing is analyzed for the case of omnidirectional blowing where a jet is injected tangentially all around the wing perimeter. The wake structure of the CC wing is compared to that of a wing without CC but at the same lift coefficient. For the CC wing, the streamwise roll up of the trailing vortex wake is delayed relative to that of a wing without CC. Turbulence modeling was found to be a critical factor in circulation control simulations. The wake structure (velocity and vorticity) of the CC wing is then compared to that of the same wing at equal lift coefficient but without CC. The lift for the case without CC is generated by placing the wing at the proper angle of attack. Using commercial software Fluent6.3 the aerodynamic phenomena and performance characteristics associated with the disc were determined by exercising care on the turbulence model, the computational mesh commensurate with the regions of high momentum exchange between wall jet and free shear layers.

VII. Conclusions

Progress and development of Coandă Jet and Vortex Cell have been reviewed, in view of their features and capabilities for Circulation Enhancement and Circulation Control. The main objectives are to gain an in-depth insight on the fundamental principles of Coandă-jet, its feasibility and practicability and to identify salient features essential for its optimal utilization. Fundamental analyses and CFD numerical experiments provide insights for understanding the physics of the problems, and fundamental and applicatory experiments are essential in observing the detail of the phenomena and understanding their subtlety. CFD numerical experiments have also been carried out to elaborate and verify the favorable effects of Coandă configured airfoil for enhanced aerodynamic performance and obtain some guidelines for their critical features. The choice of turbulence model and other relevant parameters commensurate with the grid fineness desired are critical, in particular since the number of grid utilized is relatively small in view of the desktop computer utilized capabilities. Some of the development and applications of Coandă-jet as elaborated in the paper is summarized in Table 1, as an extension of that presented by Djojodihardjo (2013).Parametric studies can be considered to be an essential tool for analysis and may offer some clues on relevant parameters which may be utilized in a multi-variable optimization (and to a larger scale, multi-disciplinary optimization).The introduction of Coandă-jet on both airfoils and aerodynamic surfaces results in enhanced L/D, which depends on the jet velocity or momentum coefficient. Rounding-off of the TE along with the introduction of the Coandă-jet seems to be effective in increasing L/D in airfoil specifically designed for Wind-Turbine, as exemplified by S809.Recent applications of Coandă-jet for STOL or ESTOL also indicate the need for doubly-curved trailing edge or flaps. The study on Coandă-jet application to wind turbines also shows that the maximum total energy output of Coandă configured airfoil may exceed that predicted by Betz limit.

Table 1: Summary of some Coandă Effect and Trapped Vortex Cavity Technique Development and Application [Djojodihardjo, 2013]

	Some Coandă Effect Development and Applications		Example/Remark
1	Invention of Coandă		**Examples/Applications**
2	Willard Custer, Englar and Campbell, Coandă effect aircraft		Channel Wing Aircraft; The lift is "due to the speed of air, not the airspeed"
3	John Carver Meadows Frost, Coandă effect aircraft		Avrocar
4	Enhanced lift by Coandă effect Circulation Enhancement		Boeing YC-14 and C-14 Globemaster III, Antonov An-72 Coaler, McDonnet Douglas YC-15, and the NOTAR helicopter
5	Coandă effect CCW STOL Demonstrator		Wake Vortex Wingtip-Turbine Powered CC High-Lift System
6	Co-Flow Jet		Co-Flow Jet
7	California Polytechnique Group, Marshall, de la Montanya, Lichtwardt, etc.		Combined Blowing Circulation Control Application to Extreme short take-off and landing
8	Automotive Application		Increase of base pressure, Coandă effect through exhaust gas for better traction
	Trapped Vortex Cell		**Examples/Applications**
1	Pioneers and active contributors, a.o: Roshko, Rossiter, Gharib and Roshko, TVC 2050 Research Group		without any mass flow suction the TVC did not induce flow reattachment produced by vortex shedding
2	Kasper Wing and The EKIP Aircraft		The EKIP aircraft(US Patent: No. 5,417,391) and The Kasper wing(US Patent: No. 3, 831,885)
3	European TVC 2050 Initiative		Prevention of vortex shedding and reduction of drag for next-generation thick-wing aircraft.

In the combined theoretical and numerical analyses, one is lead to come up with logical cause and effect laws as well as to find ways to carry out optimization schemes for desired design configurations. In summary, future work may look at various key issues such as the influence and the effectiveness of the Coandă enhanced lift for a comprehensive series of configurations, for axial thrust (lift), mass flow rate or torque producing mode, and the corresponding gain or changes in lift, drag (or L/D ratio), optimum configuration of the Coandă effect lift enhanced airfoil, the feasibility and practicability of Coandă configured airfoil for wind-turbine applications and the unsteadiness effect of Coandă-jet applications that may determine the success of Coandă-jet applications.

A brief review of Trapped Vortex Cavity (TVC) research shows that TVC is a promising technology, and active research is in progress for trapped vortex stabilization that constitutes the crux of the technique. Various parameters are relevant for Coandă-jet and Trapped Vortex Cavity, among others the momentum or blowing coefficient introduced to the original flow. In retrospect, Coandă enhanced lift enhancement technique has to a certain extent reached a stage for its practicability and application advantages.

ACKNOWLEDGEMENT

The author would like to thank Universiti Putra Malaysia (UPM) for granting Research University Grant Scheme (RUGS) No. 05-02-10-0928RU; CC-91933, under which the present research is initiated, and the Ministry of Higher Education Exploratory Research Grant Scheme Project Code No. 5527088, under which the present research is carried out.

REFERENCES

[1] L. Prandtl (1904), "Über Flüssigkeitsbewegung bei sehr kleiner Reibung", *Int. Math. Kongr. Heidelberg. Leipzig*.

[2] H. Coandă (1934), "Procédé et dispositif pour faire dévier une veine de fluide pénétrant dans un autre fluide", ed.: Brevet d'invention France.

[3] H. Coandă & C. France (1936), "Device for Deflecting a Stream of Elastic Fluid Projected into an Elastic Fluid", *US Patent Office*, 2,052,869, 1936, ed.: Google Patents.

[4] R.H. Liska (1957), H LISKA US Patent 2,788,534, 1957, ed.: Google Patents.

[5] D. Liska (1957), "Channel Wing Aircraft", *The Wisconsin Engineer*, Vol. 57, No. 6, Pp. 16 –19.

[6] K. Karamcheti (1966), "Principles of Ideal-Fluid Aerodynamics", *Wiley New York*.

[7] J.E. Rossiter (1966), "Wind-Tunnel Experiments on the Flow over Rectangular Cavities at Subsonic and Transonic Speeds", *ARC R&M 3438*.

[8] R.J. Englar (1979), "Development of the A-6/Circulation Control Wing Flight Demonstrator Configuration", *DTIC Document*.

[9] A. Pugliese & R. Englar (1979), "Flight Testing the Circulation Control Wing", *American Institute of Aeronautics and Astronautics, Aircraft Systems and Technology Meeting*, New York, N. Y.

[10] R.J. Englar, R.A. Hemmerly, D.W. Taylor, W.H. Moore, V. Seredinsky & Walter (1981), "Design of the Circulation Control Wing STOL Demonstrator Aircraft", *Journal of Aircraft*, Vol. 18, Pp. 51–58.

[11] M.J. Harris (1981), "Investigation of the Circulation Control Wing/Upper Surface Blowing High-Lift System on a Low Aspect Ratio Semispan Model", *DTIC Document*.

[12] R. Englar & G.C. Huson (1983), "Development of Advanced Circulation Control Wing High Lift Airfoils", *DTIC Document*.

[13] J. Harvell & M. Franke (1985), "Aerodynamic Characteristics of a Circulation Control Elliptical Airfoil with Two Blown Jets", *Journal of Aircraft*, Vol. 22, Pp. 737–742.

[14] M. Gharib & A. Roshko (1987), "The Effect of Flow Oscillations on Cavity Drag", *JFM*, Vol. 177, Pp. 501–530.

[15] R.J. Englar, M.J. Smith, S.M. Kelley & R.C. Rover III (1994), "Development of Circulation Control Technology for Application to Advanced Subsonic Transport Aircraft, Part I: Airfoil Development", *AIAA Paper*, Pp. 1160–1168.

[16] M. Gad-el-Hak (1996), "Modern Developments in Flow Control", *Applied Mechanics Reviews*, Vol. 49, Pp. 365–380.

[17] R.J. Englar (1999), "Pneumatic Aerodynamic Control and Drag-Reduction System for Ground Vehicles", Ed: Google Patents.

[18] R.J. Englar (2000), "Development of Pneumatic Aerodynamic Devices to Improve the Performance, Economics, and Safety of Heavy Vehicles", *Georgia Tech Research Institute*, Atlanta, GA (US).

[19] D. Geropp & H.-J. Odenthal (2000), "Drag Reduction of Motor Vehicles by Active Flow Control using the Coanda effect", *Experiments in Fluids*, Vol. 28, Pp. 74–85.

[20] R.J. Englar (2001), "Advanced Aerodynamic Devices to Improve the Performance, Economics, Handling, and Safety of Heavy Vehicles", *Georgia Tech Research Institute Aerospace* (US).

[21] Y. Liu, L.N. Sankar, R.J. Englar & K.K. Ahuja (2001), "Numerical Simulations of the Steady and Unsteady Aerodynamic Characteristics of a Circulation Control Wing Airfoil", *AIAA Paper*, Vol. 704, Pp. 8–11.

[22] R.J. Englar & B.A. Campbell (2002), "Pneumatic Channel Wing Powered-Lift Advanced Super-STOL Aircraft", *AIAA Paper*, Vol. 3411.

[23] N.D. Sellars, N.J. Wood & A. Kennaugh (2002), "Delta Wing Circulation Control using the Coandă Effect", *AIAA Paper*, Vol. 3269.

[24] Y. Liu (2003), "Numerical Simulations of the Aerodynamic Characteristics of Circulation Control Wing Sections (2003)", *PhD Thesis, Georgia Institute of Technology*.

[25] S.P. Frith & N.J. Wood (2004), "Investigation of Dual Circulation Control Surfaces for Flight Control", *AIAA Paper*, Vol. 2211.

[26] E.B. Keen (2004), "A Conceptual Design Methodology for Predicting the Aerodynamics of Upper Surface Blowing on Airfoils and Wings", *Virginia Polytechnic*.

[27] G.-C. Zha & C. Paxton (2004), "A Novel Airfoil Circulation Augment Flow Control Method using Co-Flow Jet", *NASA/ONR 2004 Circulation Control Workshop*.

[28] D. Moore (2005), "Wake Vortex Wingtip-Turbine Powered Circulation Control High-Lift System", *NASA Langley Research Center*.

[29] M. Shojaefard, A. Noorpoor, A. Avanesians & M. Ghaffarpour (2005), "Numerical Investigation of Flow Control by Suction and Injection on a Subsonic Airfoil", *American Journal of Applied Sciences*, Vol. 2, Pp. 1474–1480.

[30] Vortex Cell 2050 (2005), *6th EU Framework Programme for Research and Technological Development*.

[31] M.A. Naqvi (2006), "Prediction of Circulation Control Performance Characteristics for Super STOL & STOL Applications", *PhD Thesis, Georgia Institute of Technology*.

[32] B. Rose & T. Buttler (2006), "Flying Saucer Aircraft (Secret Projects)", *Leicester, UK: Midland Publishing*.

[33] S. Hall, R. Cooper & S. Raghunathan (2006), "Fluidic Flow Control in a Natural Blockage Thrust Reverser", *AIAA*, Vol. 3513.

[34] C. Tongchitpakdee, S. Benjanirat & L.N. Sankar (2006), "Numerical Studies of the Effects of Active and Passive Circulation Enhancement Concepts on Wind Turbine Performance", *Journal of Solar Energy Engineering*, Vol. 128, Pp. 432.

[35] M. Gad-el-Hak (2007), "Flow Control: Passive, Active, and Reactive Flow Management", *Cambridge University Press*.

[36] M. Mamou & M. Khalid (2007), "Steady and Unsteady Flow Simulation of a Combined Jet Flap and Coandă Jet Effects on a 2D Airfoil Aerodynamic Performance", *Revue des Energies Renouvelables CER*, Vol. 7, Pp. 55–60.

[37] De la Montanya, Julianna B. & David D.Marshall (2007), "Circulation Control and its Application to Extreme Short Take-Off and Landing Vehicles", *Paper AIAA 2007-1404, 45th AIAA Aerospace Sciences Meeting and Exhibit*, Reno, Nevada.

[38] C. Tongchitpakdee (2007), "Computational Studies of the Effects of Active and Passive Circulation Enhancement Concepts on Wind Turbine Performance", *Georgia Tech Research Institute*, Atlanta, GA (US).

[39] R.S. Donelli, F.D. Gregorio, M. Buffoni & O. Tutty (2008), "Control of a Trapped Vortex in a Thick Airfoil by Steady-Unsteady Mass Flow Suction", *7th IUTAM Symposium on Laminar-Turbulent Transition*.

[40] R.S. Donelli, F.D. de Gregorio & P. Ianelli (2008), "Flow Separation Control by a Trapped Vortex Cavity", *7th ERCOFTAC SIG 33*.

[41] F.D. Gregorio & G. Fraioli (2008), "Flow Control on a High Thickness Airfoil by a Trapped Vortex Cavity", *14th Symp.Appl.Laser Technique to Fl.Mech*, Lisbon.

[42] G.S. Jones, J.C. Lin, B.G. Allan, W.E. Milholen, C.L. Rumsey & R.C. Swanson (2008), "Overview of CFD Validation Experiments for Circulation Control Applications at NASA", ntrs.nasa.gov/archive/nasa/casi.ntrs.../20080031119_2008030041.pdf

[43] S.A.Ragab & A.-H.S. Salem-Said (2008), "A Numerical Study of the Effects of Circulation Control on the Wake of a Circular Wing", *Proceedings, Ninth International Congress of Fluid Dynamics & Propulsion*.

[44] Byung-Young Min, Warren Lee, Robert Englar & Lakshmi N. Sankar (2009), "Numerical Investigation of Circulation Control Airfoils", *Journal of Aircraft*, Vol. 46, No. 4, Pp. 1403–1410.

[45] R. Radespiel, K. Pfingsten & C. Jensch (2009), "Flow Analysis of Augmented High-Lift Systems", Hermann Schlichting–100 Years, *Notes on Numerical Fluid Mechanics and Multidisciplinary Design*, Pp. 168–189.

[46] M. Schroijen & M. van Tooren (2009), "MAV Propulsion System using the Coandă Effect", *American Institute of Aeronautics and Astronautics. 45th AIAA/ASAME/SAE/ASEE. Exhibit. USA: Denver Colorado, Joint Propulsion Conference*, Pp. 1–10.

[47] R.S. Donelli, P. Iannelli, E. Iuliano & D. De Rosa (2010), "Suction Optimization on Thick Airfoil to Trap Vortices".

[48] M.F.A. Hamid, H. Djojodihardjo, S. Suzuki & F. Mustapha (2010), "Numerical Assessment of Coandă Effect as Airfoil Lift Enhancer in Wind-Turbine Configuration", *Paper RCMEAE-131, Proceedings, Regional Conference on Mechanical and Aerospace Technology*, Bali, Pp. 9–10.

[49] B. Saeed & G. Gratton (2010), "An Evaluation of the Historical Issues Associated with Achieving Non-Helicopter V/STOL Capability and the Search for the Flying Car", *The Aeronautical Journal*, Pp. 91–102.

[50] H. Djojodihardjo & M.F.A. Hamid (2010), "Review and Numerical Analysis of Coandă Effect Circulation Control for Wind Turbine Application Considerations", *Conference on Aerospace and Mechanical Engineering, World Engineering Congress*, Kuching, Sarawak, Malaysia.

[51] T. Nishino, S. Hahn & K. Shariff (2010), "Large-eddy Simulations of a Turbulent Coanda Jet on a Circulation Control Airfoil", *Phys. Fluids*, Vol. 2, No. 12.

[52] H. Djojodihardjo, M.F.A. Hamid, S. Basri, F.I. Romli & D.L.A. Abdul Majid (2011), "Numerical Simulation and Analysis of Coandă Effect Circulation Control for Wind-Turbine Application Considerations", *IIUM Engineering Journal*, Vol. 12.

[53] A. Glezer (2011), "Some Aspects of Aerodynamic Flow Control using Synthetic-Jet Actuation", *The Royal Society A Mathematical, Physical & Eng*.

[54] J. Kweder, C.C. Panther & J.E. Smith (2011), "Applications of Circulation Control, Yesterday and Today", *International Journal of Engineering*, IJE-195, Vol. 4, No. 5, Pp. 411–429

[55] O.J. Ohanian III (2011), "Ducted Fan Aerodynamics and Modeling with Applications of Steady and Synthetic Jet Flow Control", *PhD. Thesis, Virginia Polytechnic Institute and State University*.

[56] C.L. Rumsey & T. Nishino (2011), "Numerical Study Comparing RANS and LES Approaches on a Circulation Control Airfoil", *International Journal of Heat and Fluid Flow*, Vol. 32, Pp. 847–864.

[57] R.J. Englar, S.M. Kelley, R.C. Rover III & M.J. Smith (2012), "Application of Circulation Control to Advanced Subsonic Transport Aircraft. Part II-Transport Application", *Journal of Aircraft*, Vol. 31.

[58] C. Werner-Spatz, W. Heinze, P. Horst & R. Radespiel (2012), "Multidisciplinary Conceptual Design for Aircraft with Circulation Control High-Lift Systems", *CEAS Aeronautical Journal*, Vol. 3, Pp. 145–164.

[59] H. Djojodihardjo, M.F.A. Hamid, A.A. Jaafar, S. Basri, F.I. Romli, F. Mustapha, A.S. Mohd Rafie & D.L.A. Abdul Majid (2013), "Computational Study on the Aerodynamic Performance of Wind Turbine Airfoil Fitted with Coandă Jet", *Journal of Renewable Energy*, Vol. 2013, Article ID 839319, 17 Pages.

[60] H. Djojodihardjo (2013), "Overview of Aerodynamic Surface Circulation Control: Coandă Jet and Vortex Cell", *International Congress on Chemical, Biological and Environmental Sciences*, Bali, Manuscript ID: ICCBES-SPL ISSUE-226.

Prof.Harijono Djojodihardjo (Sarjana Teknik Mesin, Institut Teknologi Bandung, 1962; M.Sc. in Mechanical Engineering, University of Kentucky, 1964; Mech.E. 1965, S.M. in Naval Architecture and Marine Engineering, 1966 and Sc.D.in Aerodynamics and Gas Dynamics, 1968,all from Massachusetts Institute of Technology).Insinyur Professional Utama (IPU, Prime Professional Engineer) certification was conferred by the Indonesian Institution of Engineers (PII) in 2009 and ASEAN Chartered Professional Engineer in September 2010 by the ASEAN Chartered Professional Engineer. He is an Academician of the International Academy of Astronautics (since 2008). In 2009 he was appointed as the AIROD Professor, Department of Aerospace Engineering, Faculty of Engineering, Universiti Putra. Formerly he was Professor of Aerospace Engineering at Universiti Sains Malaysia (2004-2008), Universitas Al-Azhar Indonesia (2005-2010) and Institut Teknologi Bandung (1989-2005), and Visiting Professor at Technische Unversitaet Muenchen (2002) and Toyohashi University of Technology (2002 - 2003), Chairman, Indonesian National Institute of Aeronautics and Space (Lembaga Penerbangan dan Antariksa Nasional – LAPAN), and Secretary, Indonesian National Council for Aeronautics and Space (DEPANRI - Feb.1999-June.2000), Adviser for Aerospace Affairs to the Vice President of the Republic of Indonesia, April-June 1998, Inspector General for Development, Technology and Strategic Industries, at the Office of the President of the Republic of Indonesia (June 1998 – January 1999), Deputy Chairman for Technology Development, The Agency for the Assessment and Application of Technology/ Badan Pengkajian dan Penerapan Teknologi (1991-1998). He has devoted a combined teaching, research, industrial and management experience totaling of 51 years since, which is a manifestation of his career objectives, strong interest, dedication and commitments in education, science and technology.