Applications of Circulation Control, Yesterday and Today

Jonathan Kweder jonathan.kweder@mail.wvu.edu
Center for Industrial Research Applications
West Virginia University
Morgantown, WV USA

Chad C. Panther chad.panther@mail.wvu.edu
Center for Industrial Research Applications
West Virginia University
Morgantown, WV USA

James E. Smith james.smith@mail.wvu.edu
Center for Industrial Research Applications
West Virginia University
Morgantown, WV USA

Abstract

Circulation control, an aerodynamic method of changing the properties of an airfoil, such as lift, camber and angle of attack, has been used in several unique ways since its inception, as an enhancement to fixed wing aircraft, in the 1960's. Early in the research venture, this technology was used on the main wing of an aircraft in conjunction with a Coandă surface, such as a rounded trailing edge or a deployable flap. Research during this time proved to be the foundation of the circulation control technology and showed that small amounts of exit jet velocity could have a large impact on the aerodynamics of an airfoil.

In the 1970's the inspirations that drove circulation control research changed from design work to optimization of the parameters which were found to have the most effect on circulation control. These studies included slot placement, favorable momentum coefficient, and pressurization benefits and determents. This research period also allowed for expansion of the uses of circulation control to submarine/hydrodynamic and rotary wing applications.

Newest research has brought on several propeller driven applications and the recent push for efficient renewable research has allowed circulation control research technologies to evolve into use in wind turbine and water turbine applications. The idea being that with circulation control the turbine can adapt easier to the changing wind velocity and direction and ultimately capture more power than an un-augmented turbine.

As with most new and novel technologies there is a process and time delay associated with their development and ultimate application. For some technologies the market, or the supporting hardware, are lacking and sometimes the technology has strong advocacies for yet to be fulfilled expectations. In most of these cases a strong idea will re-surface repeatedly until the art has matured, or the better solution is found. This paper will focus on the previously developed circulation control research, from its beginnings, as used on fixed wing aircraft, following the progression, as this technology evolved through the past five decades, to its now more widely considered potential.

Keywords: Circulation Control, Lift Augmentation, Drag Reduction

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NOMENCLATURE

AUV	*Autonomous Underwater Vehicle*	***NREL***	*National renewable Energy Laboratory*
c	*Airfoil Chord*	***NSRDC***	*Naval Ship Research and Development Center*
CC	*Circulation Control*	***NSWC***	*Naval Surface Warfare Center*
CCR	*Circulation Control Rotor/Rudder*	***R***	*Radius*
C_D	*Drag Coefficient*	***t***	*Airfoil Thickness*
C_L	*Lift Coefficient*	***TE***	*Trailing Edge*
C_m	*Moment Coefficient*	V_∞	*Freestream Velocity*
C_p	*Center-of-Pressure*	***VAWT***	*Vertical Axis Wind Turbine*
C_μ	*Momentum/Blowing Coefficient*	***V/STOL***	*Vertical/Short Take-Off Landing*
D	*Drag*	α	*Angle-of-Attack*
HAWT	*Horizontal Axis Wind Turbine*	$\Delta C_l/C_\mu$	*Lift Augmentation Factor*
L	*Lift*	r_∞	*Density*
LE	*Leading Edge*	Γ	*Circulation*
L/D	*Lift-to-Drag Ratio*	Ω	*Rotational Speed*
		μ	*Advance Ratio*

1. INTRODUCTION

Circulation control (CC) as a lift augmentation device is traditionally used on the main wing of an aircraft. This technology has been in the research and development phase for over sixty years, primarily for fixed wing aircraft with the early models referred to as “blown flaps.” The first reported use of blowing slots to control lift is attributed to H. Hagedorn and P. Ruden, in 1938, who noticed an unaccountable increase in lift at high blowing rates during investigations into boundary layer control on a flap [34]. Interest in active blowing systems increased with the advent of the turbojet engine, initially in Great Britain and France with a jet flap configuration. While the addition of energy near the surface of a lifting body can be used to increase lift, and thus circulation, by retarding boundary layer separation, most of the high lift applications are performed on specially designed wings where the addition of high velocity air can be used to control the boundary layer and to virtually extent the camber and the chord.

The flow of a fluid over curved surfaces has long been studied for a variety of applications. The most prevalent application of circulation control works by increasing the near surface velocity of the airflow over the leading edge (LE) and/or trailing edge (TE) of a specially designed aircraft wing using a series of blowing slots that eject high velocity jets of air [28]. These augmented wings normally have a rounded trailing edge, and eject the air tangentially, through these slots inducing the Coandă effect [38]. This phenomenon prolongs boundary layer separation while increasing circulation around the airfoil and thus increases the lift generated by the wing surface due to the relaxation of the Kutta condition. Initially, at very low blowing values, the jet entrains the boundary layer to prevent aft flow separation, and thus is a very effective form of boundary layer control (BLC) [20]. As blowing levels are increased, the jet continues to wrap around the Coandă surface causing a rise in the local static pressure. This pressure increase, along with viscous shear stress, and centrifugal forces, lead to jet separation from the rounded TE resulting in a new stagnation point on the lower surface of the airfoil. The direct effect of altering streamlines and stagnation points around an airfoil is lift augmentation.

Historically, the main purpose of CC for fixed wing aircraft has been to increase the lift when large lifting forces and/or slow speeds are required, such as at take-off and landing. Wing flaps and slats are currently used during landing on almost all fixed wing aircraft and on take-off by larger jets. While flaps and slats are effective in increasing lift, they do so with a penalty of increased drag and added hardware. The benefit of the CC wing is that no extra drag is created from the movement of surfaces into the airflow around the wing and the C_L is greatly increased. Note that while a CC wing may have less hardware on the wing there is the obvious addition of pumping and plumbing hardware that often obviates the value of the additional lift for all but a few applications.

In past analytical trials, an elliptical airfoil shape was used to analyze the potential fluid flow, [49] for these applications. The original theoretical methods are only applicable for frictionless, incompressible fluids, thus not truly valid for complex CC flows, due to the compression of air at the blowing slot. In 1975, further research was completed using the Theodorsen method in a potential flow analysis of 20%t/c CC-ellipse (5% camber), with a modified circular TE [25]. The analytical results showed close agreement to Kind's experimental data [28]. A Coandă simulation was later conducted which under-predicted the decay of the maximum jet velocity [9].

From previous experimentation, four main benefits were achieved by using an active circulation control method on fixed wing aircraft to control moment augmentation [4] [21]. These benefits are:

1. Very small movement, or even non-moving, control surfaces are required [14],
2. Lift augmentation can be achieved, independent of the airfoil angle-of-attack, and can virtually change the airfoil's apparent camber/angle-of-attack
3. Jet turning angle no longer limited by physical jet exit angle/flap deflection angle [18],
4. Very high force augmentation can be achieved per unit blowing momentum input [20].

Following the application of this technology to fixed wing and rotary wing aircraft, it became increasingly more attractive to consider for other areas such as marine propellers and lifting surfaces, passenger and transport automobiles, as well as wind turbines and water turbines. The use of this technology has also been seen to advance other technologies because of the need for smart materials, such as for piezoelectric valves [46]. This literature survey contains research documented in other recent surveys [33] [57], as well as summarizes these previous studies and reviews the findings as they contribute to the further advancement of circulation control technology.

2. EARLY CC RESEARCH (1960'S-1970'S)

Circulation control has been implemented in various applications since its inception. Among these applications that have been studied in the past are high lift fixed wing aircraft, vertical/short take-off and landing aircraft (V/STOL), and anti-torque systems for rotorcraft.

In 1969, wind tunnel studies of three 20% t/c elliptical airfoils for stowed rotor applications were completed at the NSDRC. Several TE configurations were examined including three TE shapes (true ellipse, circular), TE radius (R/c = .019, .038), and chord-wise location of slot (x/c = 0.813, .922, .934). These results showed, that when the blowing coefficient is varied ($0 \leq C_\mu \leq 0.32$) and angle of attack is held constant, a violent LE stall occurs only correctable with a compensational change in the α, called an α-stall [57]. A second stall phenomenon occurs when the C_μ is held fixed and α is varied through a number of positions ($\pm 10^o$). This test also produced a TE stall which was not nearly as severe as the aforementioned LE stall.

In 1969, a series of testing scenarios of V/STOL and landing vehicles was conducted at Washington University in order to study the low speed applications and wind tunnel capabilities. It was shown through this study that, there is a minimum speed, determined by wind tunnel geometry, in which the flow seems to breakdown and the testing is no longer valid. Testing below this minimum tunnel velocity produces recirculation flow within the tunnel which is also shown to be a function of the downwash, configuration of this model and relative size of the model [41].

In 1970, at West Virginia University (WVU), a study was conducted on two circulation controlled cambered airfoils, for fixed wing aircraft applications, Model A (20% elliptic/c ellipse, 5% camber, and true elliptical TE) and Model B (20% elliptic/c ellipse, 5% camber and a modified circular TE R=5.8%c) in the hopes of proving that the addition of a high velocity jet of air ejected tangentially around the airfoil would produce a greater lifting force on the airfoil due to the Kutta-Joukowski theorem. This theorem, shown in Equation 1, states that the overall circulation (Γ) around the airfoil is directly related to the lifting force (L) when expressed in terms of the freestream velocity (V_∞) and fluid density (ρ_∞) of the free stream flow [26].

$$L = \rho_\infty V_\infty \Gamma \qquad \textbf{EQUATION 1}$$

It was found that Model A produced a lift-to–drag ratio (L/D) of 30 and Model B produced a ratio of 55 proving that circulation impacted the lift directly, and the experiments also determined that the TE shape is the major parameter that should be considered when dealing with a CC airfoil. For low freestream velocity (Re ≤ 500K) a circular/rounded TE shape provides better lift augmentation ($\Delta C_l/C_\mu$) while at high freestream velocities (Re > 1×10^6), an elliptical TE shape is the optimal choice.

Very few stall experimentations were conducted in past work with circulation control airfoils, however, studies were conducted on a 20% t/c elliptical airfoil (5% camber) and the momentum coefficient (C_μ) was varied from 0.006 to 0.119, with a constant free stream velocity (V_∞) of 100 m/sec [26]. Stall angles of this airfoil were increased from nine to fourteen degrees through this range of C_μ. This stall study did not, however, take into account LE or TE separation effects, only the effects of the entire suction surface of the airfoil. This airfoil's TE was also unaltered, so the Kutta Condition still held true.

The pitching moment (C_m) and center-of-pressure (C_p) of the experimental model are very important parameters when testing the stall angles in a wind tunnel environment. In 1970, two models were examined for the change in the pitching moment and center of pressure. The results concluded that at three different angles of attack, neither of these two parameters is significantly affected by a change in lift coefficient [26].

In a follow-up study conducted at WVU, Model B, from the experimentation conducted by Harness, was examined in greater depth as to how the rounded trailing edge of the airfoil impacts the addition of lifting forces on the aerodynamic body, for fixed wing aircraft ([36]. Through this study it was shown that the airfoil tested could attain a maximum C_L of 4.58 with a C_μ of 0.17. The author also claims that the rounded TE radius of 5.8% c was as optimal a design as could be used on this particular airfoil. The author further states that the rounded trailing edge is the most important parameter when dealing with CC airfoils.

In 1971, research was conducted to design a non-deflecting stern plane for a submarine, by applying CC technology. This was one of the first instances where an application of CC technology was studied for a purpose other than fixed wing aircraft [12]. Elliptic hydrofoil sections with a rounded trailing edge were used for this experiment. Each of the models had upper and lower tangential blowing slots. The same profile of the existing stern plane was used to minimize any additional interference. A second design is also mentioned with end plates added to reduce induced drag which showed an overall improved performance. Studies showed that the stern plane with CC activated provided a reliable solution to submarine stability, however, optimizing the endplates by adding camber to increase the aspect ratio was predicted to make an even better improvement.

This work allowed for the creation of a non-dimensional relationship to be established between ejection slot height, airfoil chord, and trailing edge radius. This information became important in choosing an airfoil profile for CC applications, as there was a region where the Coandă operation was most effective. This idea, postulated by Englar, can be seen in Figure 1, where airfoils which were designed to fall within the shaded region would be able to take more advantage of the benefits of the CC technology than ones which fell outside of this region.

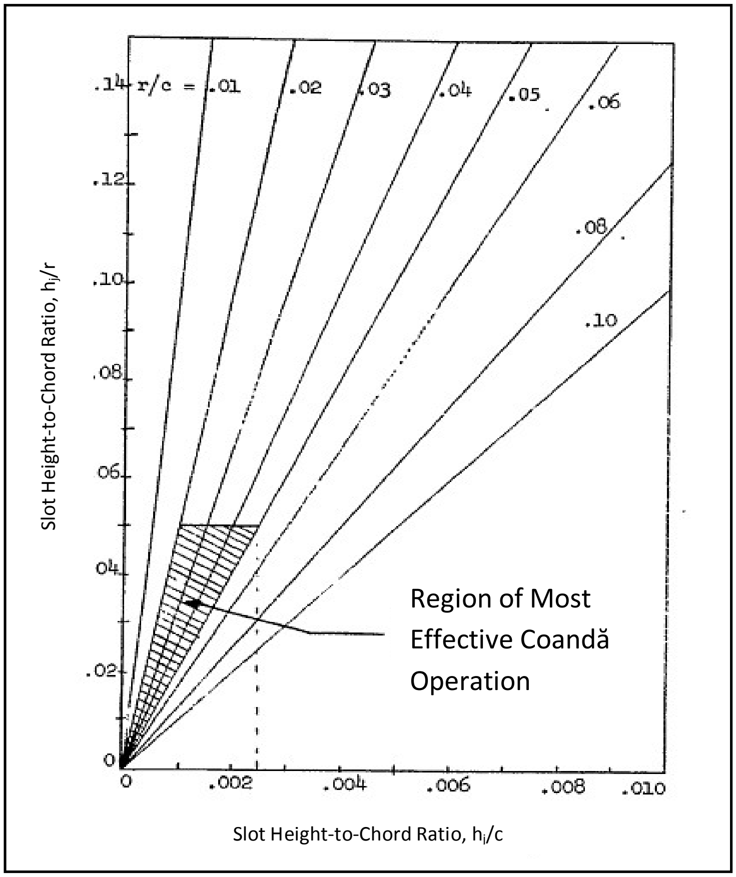

FIGURE 1. Englar's Original Hypothesis of the Region of Most Effective Coandă Operation [11].

Adding to the studies conducted by Harness and Myer, further experimentation of Model B was conducted in 1972 using the principle of unsteady flow to study the effect of pulsing the CC jets on and off in a repetitive manner [27]. This investigation showed that modulating the air to feed the exit jets provided a 25% decrease in mass flow rate and still provided a 15% overall increase in C_L. This study further indicated that the feasibility of CC for use in fixed wing aircraft was not as dependant as previously thought on the addition of large weight additions of mass from regulation and pressurization equipment.

With the introduction of CC to rotary aircraft, a study conducted at WVU was done on a shrouded propeller in order to attempt to increase the static thrust of the propeller. The apparatus in this study used CC theory and the addition of blowing slots around the propeller shroud to change the effective velocity and pressure of the flow that the rotor interacts with [7]. The results of this study concluded that the CC shroud produced the effect of being a cambered shroud while CC was activated, as well as, successfully increasing the overall thrust produced by the motor at increasing C_μ.

CC was applied to a helicopter rotor model in 1973, and tested by means of installing the model into a wind tunnel. This “first generation” helicopter application demonstrated the use of CC over the entire rotor field as well as demonstrating rotor trim, lift augmentation, and maneuver moment generation through the use of cyclic blowing [56]. This was one of the first steps into applying circulation control principles to rotary powered aircraft.

The second instance of attempting to apply CC principles to rotating bodies was made in 1973 at the Naval Surface Warfare Center (NSWC). This study examined the inherent issues with using CC on a rotor, such as, boundary layer separation due to an adverse pressure gradient, the inaccuracy of measurements, and the use of flow visualization methods. This study showed that the use of pressure taps on the model to measure lift and drag forces, is a more accurate way of collecting the necessary two-dimensional data and more practical than using a conventional force balance method [10].

Again in 1975, two-dimensional CC wing sections were examined and found to produce maximum lifting coefficients of three times that of an unaltered airfoil with a sharp TE [15]. These models were fabricated using the existing NACA shape profiles (NACA 66-210 and NACA 64A-212), removing the sharp TE and replacing one profile with a rotated flap configuration and the other profile with a circular TE of radius 0.875 inches. At various angles of attack ($-16^\circ \le \alpha \le 15^\circ$) and momentum coefficients ($0 \le C_\mu \le 0.24$), the modified NACA 66-210 and NACA 64A-212 models produced C_L values of 5.5 and 5.95 respectively, at a C_μ of 0.20.

At the Aviation and Surface Effects Department, in conjunction with the David W. Taylor NSRDC a 15% t/c CC elliptical airfoil section with slots at both LE and TE blowing slots was evaluated in a subsonic wind tunnel. The goal was to determine its potential for use in conjunction with a high-speed (300-400 knot) helicopter rotor system. Fore-and-aft slot utilization was determined by local flow direction over the blade as it revolved around the azimuth. Aerodynamic performance was not affected by the addition of an un-blown LE slot except beyond the usable positive α range. Some loss in lift and an increase in drag were noted in the results. At equal plenum pressures, simultaneous blowing from the LE and TE slots resulted in a decrease in C_L, an increase in C_D, and a more positive C_m when compared to TE blowing alone [40].

Another series of evaluations were performed on a 20% t/c CC-ellipse in 1975, for use on fixed wing aircraft. In this testing scenario, an elliptical airfoil was tested at subsonic speeds in a two dimensional wind tunnel environment which produced C_L of 5 while C_μ was 0.24. This C_L showed a similar improvement in the L/D of the activated circulation control model, reaching a maximum value of 30 [3].

In the mid 1970's, a theoretical analysis was completed on arbitrary airfoils, augmented to include CC capabilities in order to predict the blowing slot characteristics for a given airfoil at given operating conditions. This research proved to have a powerful effect on the study of CC in that it used potential flow, laminar boundary layer, turbulent boundary layer and turbulent wall jet theories applied together in order to approximate the geometry needed for the CC exit slots [25]. The application of these aerodynamic theories to circulation control provided a basis in which to design an augmented airfoil for a specific use without the need for several failed designs, including physical tests, and ultimately redesigns of the particular CC airfoil.

Another rotary application of CC was conducted at the David W. Taylor NSRDC in 1976, where hardware was applied to a high speed helicopter blade and tested during reverse blowing conditions (i.e. while the rotor is in retreat in comparison to the freestream velocity along the rotary path). This study involved wind tunnel testing of an elliptical airfoil (root section: 20%t/c, 5%camber, tip section: 15%t/c, 0%camber) with both LE and TE blowing slots in which CC was activated and seen to improve the overall performance of the helicopter during hover applications and through advance ratios of 4.0 [42]. This system also proved beneficial while flying through the critical advance ratio of 0.7. Equation 2 defines the advance ratio (μ) of the rotor, using the freestream velocity (V_∞) related to the rotational speed (Ω) and radius of the propeller (R).

$$\mu = \frac{V_\infty}{\Omega R} \qquad \textbf{EQUATION 2}$$

In the late 1970's circulation control was applied and used on the TE of a fixed wing aircraft, specifically on the A-6 flight demonstrator [16] to achieve larger C_L values at times of need such as take-off and landing. Wind tunnel testing was completed using a NACA 64A008.4 (modified) model and test case ranges included ($0 \le C_\mu \le 0.30$) and ($-4^\circ \le \alpha \le 22^\circ$) at a Re of 1.9×10^6. In this testing, C_L of 6.5 was found in two-dimensional testing, and a three-dimensional C_L was found to be a factor of 2.2 greater than non-blowing cases (C_μ=0).

FIGURE 2. A-6 Flight Demonstrator [42].

In 1976, the inaugural CC flight demonstrator was built and flown at WVU. The pioneer plane was equipped with a retractable Coandă surface on the TE of the aircraft, as shown in Figure 3 [30]. It was found that CC flap deployment increases the wing chord by 20% for increased performance with blowing. The flap is articulated with a bell crank but is not rigidly connected to the piano hinge at the sharp TE. Its sliding connection allows the rounded TE to thermally expand up to ½" when the hot gas bleed air is routed from the auxiliary turbine situated in the rear seat of the aircraft. The flight test of this aircraft produced lift augmentation increases of the local C_L value from 2.1 to 5.3 with a C_μ of 0.12.

FIGURE 3. Trailing Edge Coandă Surface Extended From WVU Flight Demonstrator [30].

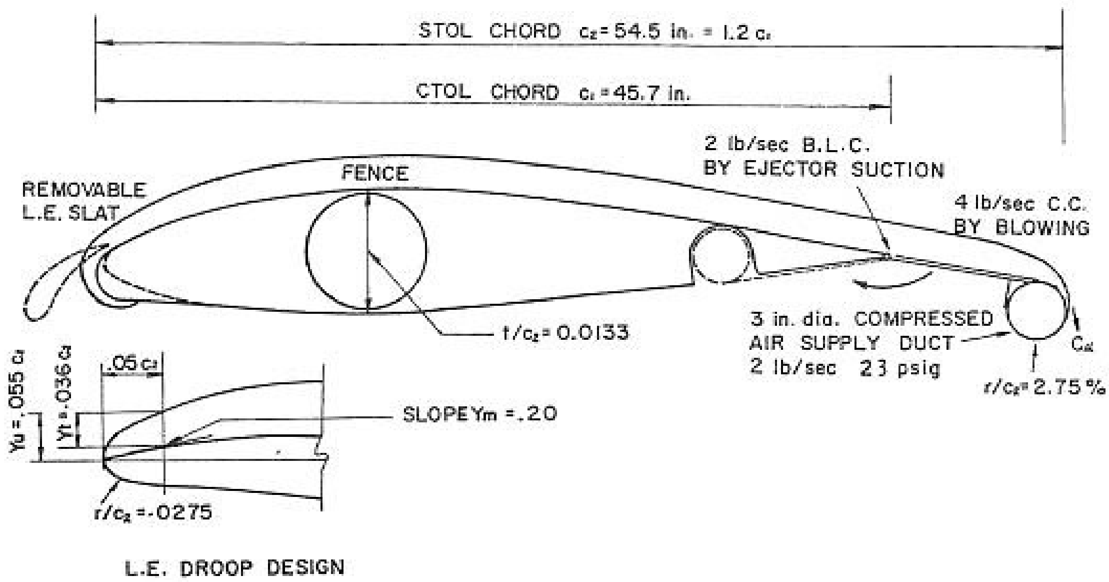

FIGURE 4. Schematic of Trailing Edge Coandă Configuration of WVU Flight Demonstrator [30].

3. MID-CYCLE OF CC RESEARCH (1980'S)

As the development of CC technologies continued, research and experimentation gained regard in the scientific community. With the new understanding of CC technology, its application and uses of CC technologies began to expand from simply being an addition to existing aircraft to being a significant design factor to improve performance of rotary powered aircraft. Also gaining interest was novel ways of pressurizing for the CC plenums located inside the airfoils, as it was shown that the addition of large scale pumping devices often negated the value the additional lifting forces achieved by adding circulation control.

With the introduction of CC rotor blades, in the 1970's, a study was designed to look at the differences in the noise levels of using such high lift devices in place of conventional helicopter blades. The testing models used were the circulation control rotor (ejects high velocity jets of air tangentially around a rounded trailing edge), X-Wing (designed to stop mid-flight and act as a fixed wing at high forward speeds, while utilizing CC technology on the upper surface), and a control scenario (a conventional helicopter rotor). In studies which used similar rotational speeds, advance ratios, and forward speeds, the X-Wing rotor showed the most promise for eliminating blade/vortex noise as well as impulse noise, both common with conventional helicopter rotors. In testing the CCR, it was found that there was an abundance of broadband noise at high blowing velocities which produced high decibel levels while testing [35].

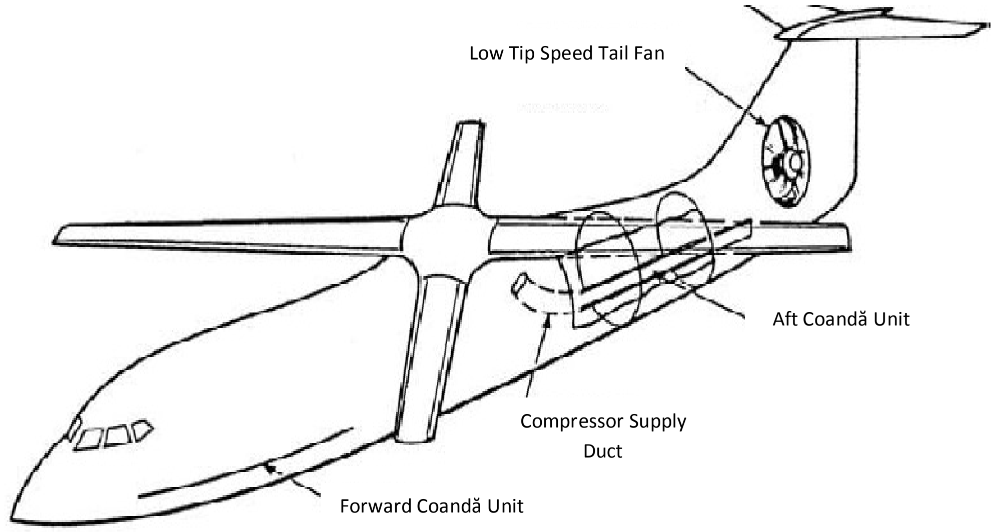

FIGURE 5. X-Wing Configuration and Supply Compressor.

A study conducted at WVU optimized the wall jet velocity used for CC applications in STOL aircraft. The information found in this experiment showed that the addition of a Coandă surface and jet ejectors improved the CC performance. This study also showed that the need for a "stowable" Coandă surface needed to be examined and implemented so that the CC surface would be able to be taken out of the flow during cruise conditions when the high values for lift were not needed [31].

Two-dimensional wind tunnel tests were conducted on a 20% t/c elliptic airfoil which was equipped with both forward and reverse blowing slots. This model was tested between momentum coefficient values of 0.0 to 0.4, and included some tests with leading edge slot activation. The results of this study contributed fundamental knowledge to the understanding of the behavior of Coandă surfaces and Coandă flows. This research proposed that the exit jet is a flow of highly concentrated vortices and may explain the strong entrainment experienced with Coandă flows [52].

In 1986, a 15% t/c ellipse with interchangeable TEs was studied in Stanford University's low-speed wind tunnel in order to obtain C_L and C_μ data to compare to the NSRDC studies completed several years previous [43]. Although a similar model was used, a leading edge activation slot was added to the model as well as a wall blowing slot was introduced at 0.85 x/c to reduce the three-dimensional effects on the model 3D effects are large in part caused by extreme pressure gradients at the junction of the model and endplates/tunnel walls.

Testing was conducted with the LE and TE slots activated. LE slot activation was shown to induce a positive lift enhancement at high blowing rates ($C_\mu \geq 0.10$). Two types of flow fields were observed due to the LE activation. In one situation, the flow folded over the top leading edge and the second showed the jet continued over the lower surface. The combination of dual slot activation showed the availability of a positive lift enhancement, although further investigation needed to be completed [43].

During a three year stretch during the mid 1980's, a series of experiments were conducted by NSRDC (1984) and Lockheed Martin (1987), the first of which attempted to redirect the engine thrust of an aircraft to be used to deflect the flow around a Coandă surface on the TE of a wing. An above wing mounted propulsive device was used in this wind tunnel experiment, and in a series of full-scale tests a deflection angle of 90 degrees was achieved, producing a C_L of almost 6.0 [17]. This system also achieved lift augmentation equal to, or in some cases greater than, that of the multi-flap systems commonly used in commercial aircraft and offered this similar augmentation without the addition of weight and complexity of several moving parts. In 1987, the upper jet deflection apparatus was combined with a flow entraining system (CC wing) which demonstrated the ability of the exhaust flow and the circulation control jet to work together to increase the lifting capability of the aircraft even further than the experiments conducted in 1984, resulting in a C_L upwards of 7.0 [17].

1987 brought about a study which combined laser velocimetry measurement and surface pressure measurement of aerodynamic forces on an airfoil model with a circular wall jet. This model had a slot thickness-to-chord ratio of 0.002 and was examined at momentum coefficients of 0.1 and 0.03. Using both of these methods to measure the aerodynamic forces provided a background in which to accurately validate and generate CFD data [39].

Secondly, in 1987, the effects of blown jets on the aerodynamic forces of cambered elliptical airfoils were studied using models with a chord of 0.66m a span of 0.51m and an ejection slot height of 0.005m. Each of these three models examined a different effect of the application of circulation control technologies to an airfoil model. One model used a single plenum to supply air to the circulation control slot, while a second model used two plenums, supplying air to two ejection slots. The results measured from these models were compared to reveal that the use of two blown jets is more effective than a single blown slot in some cases. The fourth model, "the rotating cylinder" model proved that the relative location of the two jets also had an impact on the aerodynamic forces and the maximum C_L/C_D ratio was obtained by limiting the flow of the second slot to allow the first slot to attain flow attachment [24].

After completing the previous study [31] of CC in attempting to optimize the jet velocity, the next step in the process of studying this technology at WVU was to analyze the thrust savings that CC could provide to aircraft using high lift wings. It was found that high lift devices such as CC and boundary layer control (BLC) apparatuses have a distinct upper C_L limit that can be achieved. Any attempt to exceed this optimum C_L, as in high speed applications, would cause rapid deterioration of the BLC objectives [32].

4. NEWEST CC RESEARCH (1990'S–2000'S)

In this section, CC techniques are shown to have become more predictable, as well as, they are shown to be productive in several previously unresearched scenarios, including water/other fluid mediums, vehicular uses other than aircraft (i.e. tractor trailers and automobiles), and wind turbines. It can also be shown that the future uses of CC are expansive, in comparison to the original ideas for the uses of this technology. Further research in this period includes the ability to reduce the amount of additional hardware to the original system and attempts to enhance the control of the system, or increase its effectiveness.

In an assessment of using a stopped rotor in conjunction with CC in the early 1990's, a study was performed to analyze and predict the effects of the addition of CC. This study produced a software tool which predicts trade-offs in sizing appropriate to stopped rotor systems based on horsepower, forward flight speed, mass flow requirements as well as it predicts some of the transition performance expectations while the aircraft travels at high speeds [48].

In 1996, the Circulation Control Rudder (CCR) was tested in an attempt to improve hydrodynamic characteristics of control surfaces found on ships. Water-channel testing of a modified NACA 0015 was completed at Wuhan Transportation University in Wuhan, China; 2-D and 3-D aerodynamic coefficients were analyzed at various momentum coefficients ($0 \le C_\mu \le 0.63$ and AoA ($0^\circ \le \alpha \le 24^\circ$), Results showed that the lift developed by a CC section can be easily and rapidly changed simply by varying the supply of blowing water [47]. The section shape facilitated the attainment of high structural stiffness. This method was able to generate a large lift force at small or even zero angle of attack while using only minimal values of C_μ (≤ 0.05).

A second scenario was tested in this experimentation which included the endplates and longitudinal v-grooves engraved in the Coandă surface. A high C_L was produced by the CCR with trailing-edge jet blowing at a zero degree angle of attack, and the lift coefficient of the CCR at a fixed angle of attack increased with jet momentum. The maximum of L/D occurred at zero degree angle of attack. Based on this, it could be used in ships to improve the maneuvering performance, especially when the ship sails at low speed. When reaching its maximum L/D, the lift decreased abruptly with further increasing jet momentum, known as C_μ-stall. With endplates installed, the C_D and L/D characteristics were improved, and the lift at relatively large α increased. Also, with the introduction of longitudinal v-grooves, the lift and drag forces were smaller, but the lift-to-drag ratio was shown to be greater [47].

In 1996, at the Georgia Tech Research Institute (GTRI), a new application of CC was envisioned. It was hypothesized that because the modern ground vehicle, automobiles and long haul tractor trailers, are influenced greatly by vortex shedding and separated flow fields, the addition of CC technologies might positively impact the fuel consumption and efficiency of these vehicles. In such applications, lower levels of C_μ would be used as BLC, rather than lift augmentation, to reduce separation, decreasing the vehicle's C_d leading to a direct improvement in fuel economy. In the push for greater fuel economy and reduction of the use of fossil fuels, the application of CC technologies to ground vehicles is just one of many solutions being considered. Wind tunnel tests of a generic fiberglass automobile model, showed a 35% reduction in overall drag in comparison to an already streamlined vehicle without circulation control. Another facet of this research concluded that the application of lower surface blowing, as opposed to upper surface activation can provide an increase in down-force on the vehicle as well as reducing the instability of the automobile while in a yawing motion, thus showing that active blowing can be used to restore the lateral stability of the model [19].

Although CC technology was first envisioned to be a productive system for enhancing lift in any fluid medium the vast majority of studies up until the mid 1990's examined the system within the constraints of using airflow as the pressurized fluid medium. In 2004, a water tunnel experiment was conducted in the Large Cavitation Chamber, located in Memphis, TN. This study used a circulation controlled wing having a 20% elliptic cross section, an aspect ratio of 2, and both upper and lower surface jet exit slots. This model also employed a slight amount of taper, overall, 0.76 from root to tip. Unlike the previous tests which use air as the pressurization medium, this model provided a visual representation of the behavior of the exit jet at various angles of attack and plenum pressures [44]. One unique finding of this particular research was the fact that when cavitation was forced to occur on the Coandă surface, there was no abrupt stall of the airfoil. The model showed signs of a slow, even decrease in the lifting forces. This indicated that the reduction of the pressure around the exit jet and Coandă surface, while decreasing the lifting force as expected, will not become detrimental, and will still allow the propeller, or airfoil to produce a lifting force, even at conditions of higher speed, greater depth/altitude, and increased pressure. Also shown in this study was the availability to produce a positive lifting force at a geometric pitch angle of negative 40 degrees. In comparison to ship surfaces of the same geometry, this particular CC augmented rudder produced a lifting coefficient of 3.0.This lift increase was nearly double that of its counterpart [44].

The effects of pulsed vortex generator jets on a naturally separating low-pressure turbine boundary layer were studied in 2002 at the Advanced Flight Systems Department of Lockheed Aeronautical Systems Company. These vortex generator jets were pulsed over a wide range of frequencies at constant amplitude. The resulting wake loss coefficient versus pulsing frequency data documented a minimal dependency on amplitude. Vortex generator jets were shown to be highly effective in controlling the location of laminar boundary layer separation. This behavior suggested that some economy of jet flow may be possible by optimizing the pulse frequency for a particular application. At higher pulsing frequencies, when the flow is fully dynamic, the boundary layer was dominated by periodic shedding and separation bubble migration [8]. This study opened the door to research into pulsing flow circulation control applications as well as conservation of onboard CC pressurization.

Pneumatic control and distributed engine technologies were explored by NASA Langley Research Center in 2003 as a means to maximize performance of a new civil aircraft concept called the Personal Air Vehicle [29]. A morphing nacelle was designed capable of enhancing propulsive efficiency throughout the flight envelope. Initial experimental investigation of this technology used CC applied at the inlet and exit nozzle of a shrouded fan, similar to previous experiments conducted at WVU [7]. A powered model shrouded fan was tested on a static thrust cell at GTRI in order to quantify any performance brought by CC enhancements.

Tests were conducted both in and out of ground effect, determining the effectiveness of the CC adaption to enhance propulsive efficiency. The tests showed that the inlet CC device was effective at alleviating inlet stall in static operation but showed limited performance enhancements. This technology did, however, prove to be effective at reducing peak ground pressure when operating at greater heights. An enhanced mass flow into the nacelle was noted with CC activation, showing a possible propulsive efficiency augmentation to be considered for further research.

In 2004, again at the NSWC, an elliptic airfoil section (17%t/c, 1% camber) was evaluated to determine the low speed characteristics of performance. This model was tested with both upper and lower CC surface blowing slots and at a zero angle of attack so as to analyze the blowing efficiency of the system. This model produced a C_L of 3.6 during employment of the upper slot exit jet, while the lower slot produced a C_L of -4.0. This result shows that using a negatively effective camber on a circulation control airfoil produces a greater lift augmentation ratio and lifting force [3].

Similar studies to that of the fiberglass model automobile were conducted in 2005; however, the circulation control system was directly applied to a tractor trailer and examined in real use conditions, driving on the interstate. With the use of heavy vehicles to transport goods, and the fact that a typical tractor trailer averages 175,000 miles a year, fuel costs alone average upwards of $40,000 each year [21]. The application of circulation control technologies to these types of vehicles, although a small benefit in comparison to traditional CC applications can be quite meaningful.

The preliminary tests of this type of application were conducted in a wind tunnel environment in order to get an idea of the practicality and feasibility. The next step in the testing process lead to an actual tractor trailer being retro-fitted with appropriate circulation control hardware along the length and around the back door of the trailer. A second replica tractor trailer was also examined in order to produce a baseline comparison test.

The results show that activation of certain blowing slots can reduce drag (in the wind tunnel model) of up to 84% by preventing the flow separation at the rear end of the vehicle. It was also noted that the activation of top blowing slots, only, can increase the lifting force experienced by the wheels of the automobile and thus increase its fuel economy [23]. Several ideas for the supply of circulation control pressurized air, without the addition of heavy, complicated aftermarket parts, include a turbo/super charge onboard or already existing auxiliary engines (such as cabin generators and refrigeration motors).

In 2006, a rapid predictive method was studied for the implementation of circulation control techniques at the GTRI. In this study, two-dimensional circulation control performance calculations were made using the Navier-Stokes Equations for fluid flow. Coupled with a computer code to compute and predict circulation control airfoil characteristics, this method set out to predict the interaction between variables involved with circulation control systems. Using flow visualization, quantitative, and qualitative methods, it was possible to compare the aerodynamic forces achievable by adding circulation control. Although the particular experiment is only useful for selected ranges of variables such as pressure and density, the overall modeling can be used to predict the effect of adding circulation control to a model operating at any range of variables, so long as the variable are all called out at the beginning of the simulation [37].

Later in 2006, the aerodynamic performance of a wind turbine rotor equipped with circulation enhancement technology was investigated using a three-dimensional unsteady viscous flow analysis [51]. This study used a trailing-edge blowing slot and a gurney flap on the model. The National Renewable Energy Laboratory (NREL) horizontal axis wind turbine was used as the baseline configuration. At low wind speed (7 m/s) where the flow is fully attached, it was shown that a Coandă jet at the trailing edge of the rotor blade is effective at increasing circulation resulting in an increase of lift and the thrust force in the chord direction. An increased amount of net power generation compared to the baseline configuration was also seen for moderate blowing coefficients ($C_\mu \leq 0.075$). The application of a passive Gurney flap was found to increase the bound circulation and produce increased power in a manner similar to the Coandă jet. At high wind speed (15 m/s) where the flow separated, both the Coandă jet and gurney flap become ineffective in increasing the performance.

In the interest of forwarding the study of circulation control effects in alternate fluid mediums, an experiment was conducted at the University of Strathclyde, England, implementing a modified marine propeller duct with circulation control capabilities. The study focused on using this propeller duct to eliminate the use of conventional control planes on autonomous underwater vehicles (AUV's). The use of this altered propeller duct indicated an effective increase of the maneuvering force produced, of about 600%, and also increased the efficiency of the overall ability to maneuver the craft by 9.5% over the ability of the conventional lifting surfaces [53]. This study further showed the availability of a CC application to a wider array of uses, particularly uses involving hydrodynamics and other water applications.

In 2006, at WVU, a conceptual design of a new helicopter blade, with the addition of both LE and TE blowing slots, was studied, in the hopes of using this technology to reduce or eliminate the need for a swash-plate design. This application uses CC slots on the helicopter blades to increase the lifting forces of the aerodynamic surfaces, thus increasing the payload of the system while eliminating the need to articulate the blade angle continuously throughout the rotation of the blade. This new design would eliminate many mechanical complexities associated with the aforementioned swash plate configuration. Although this design is still in the development stages, it predicts that the reliance on the major limiting factor and failure point of helicopters, the swashplate, can be reduced or even eliminated [5].

Further research work was conducted at NSWC in 2006, on the dual LE and TE slotted CC wing, in the Large Cavitation Channel in Memphis, TN. In order to measure the performance of the 20% t/c elliptic airfoil (rounded trailing edge) force measurements via a 6-component load cell balance and laser Doppler velocimetry data was taken in the wake of the airfoil [10]. An extensive number of tests were run in order to produce characteristic loading of the model due to angle-of-attack, slot exit velocity, and cavitation impact. With the results of this test documented, a computational model was envisioned to be built, simulated, and compared to the data found in testing in order to get a general understanding of the effect of CC on several different cross-sectional hydrodynamic surfaces.

In another study of a unique implementation of circulation control sciences, active (leading edge and trailing edge slots and exit jets) and passive (Gurney Flap) CC systems were applied to a horizontal axis wind turbine (HAWT). In the application of a leading edge, the results showed that at high wind speeds the enhancement with circulation control techniques breaks down and is no longer applicable. When the “passive” Gurney Flap system as well as the trailing edge activated slot were employed on the model, a circulation increase around the airfoil was observed and the overall power generation capabilities experienced a net increase over the unaltered model.

The activation of trailing edge blowing slots proved to have a larger aerodynamic force output as well as a larger power output available than the model employing a “passive” Gurney flap system. However, the application of the Gurney flap without the need for an external pumping system gives it versatility in applications where no additional weight or added complex hardware is allowable [50]. This selected study, although focusing on HAWT configurations, can also be implemented in vertical axis wind turbines (VAWT) as well as water turbines and coaxial, multi-stage compressors.

A more recent testing scenario, of near surface actuation circulation control for use on a rotorcraft main rotor was conducted at WVU [6]. Again, in this scenario, an external compressor was used to pressurize the plenums of the experimental model to 10-15 psig, resulting in a slot exit velocity of 1000 ft/s. The circulation control velocity has a bearing on several factors including slot height, slot length and plenum pressure. As with Englar’s work, this study produced results which proved a lift coefficient in excess of 5.0 is achievable. Also in this work, the response times of a circulation control model of a 10:1 elliptical airfoil was determined to be 55-60 ms.

In 2009, a research program emphasized the development of CC active flow control concepts for high-lift augmentation, drag control, and cruise efficiency. The ability to consistently predict advanced aircraft performance requires improvements in design tools to include these advanced concepts. Validation of these tools was based on experimental methods applied to complex flows that go beyond conventional aircraft modeling techniques.

The experimental data highlighted the physics of separation and circulation related to activation of CC on high lift and drag-control airfoils [22]. Lift coefficients over 8 at $\alpha=0°$ was demonstrated, as well as a drag increase or decrease by variation in blowing. In analysis of these test results, existing CFD codes were employed to assist in evaluation of tunnel effects, such as wall interference, wall juncture flows, possible 3-dimensional interference, and resulting induced downwash.

Finally in 2009, preliminary studies were conducted at West Virginia University to add circulation control technology to a vertical axis wind turbine (VAWT). Selection of a circulation control airfoil to be used on an H-Type VAWT Performance predictions were studied after adding circulation control to a computationally simulated model. C_μ values of 0%, 1%, and 10% were studied over a range of solidity ratios, 0.01-0.4. It was found that the overall power output performance of the turbine would be increased 24% at a blowing coefficient of 10% [54]. This work continued through the implementing a momentum model of the wind turbine in order to begin developing the control algorithms needed to use circulation control most efficiently around the turbine blade's path. The initial two-dimensional version of the model proved successful in modeling the interaction and effects of the turbine and its wake region [55]. Below in Figure 6, the model of the VAWT is shown which shows the vortex production at the 90 and 270 degree position of the rotation, as well as the wake confinement to the original diameter of the turbine.

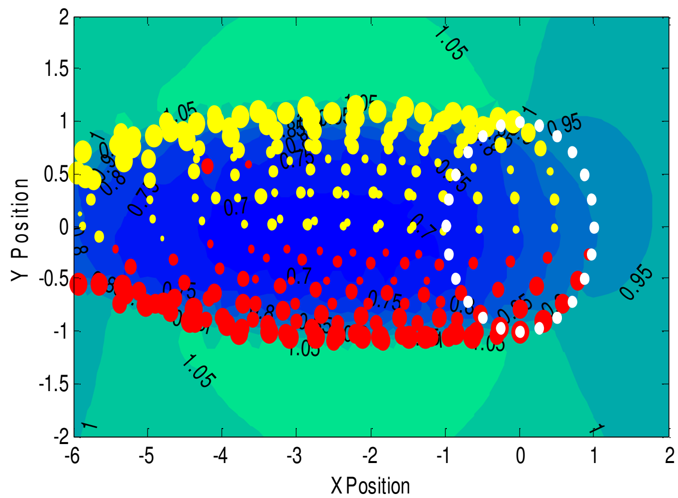

FIGURE 6: Vortex Model Velocity Field with Vortices and Blade Positions [55].

Through the study of the applications of circulation control and previous experimentation, it was possible to add further specific airfoils to Englar's original three dimensional airfoil comparison study in 1971 to see exactly where all the models and applications fall in comparison to the "region of most effectiveness," see Figure 7, below. In this figure, the previous noted work has been added to show how each compares to the most effective circulation control region. This figure can be very powerful in selecting future airfoils for circulation control applications, as the most important airfoil dimensions (h_j, c, and r) are related to one another. This reduces the need to research an airfoil profile in a wind tunnel environment before selecting the appropriate model for the application.

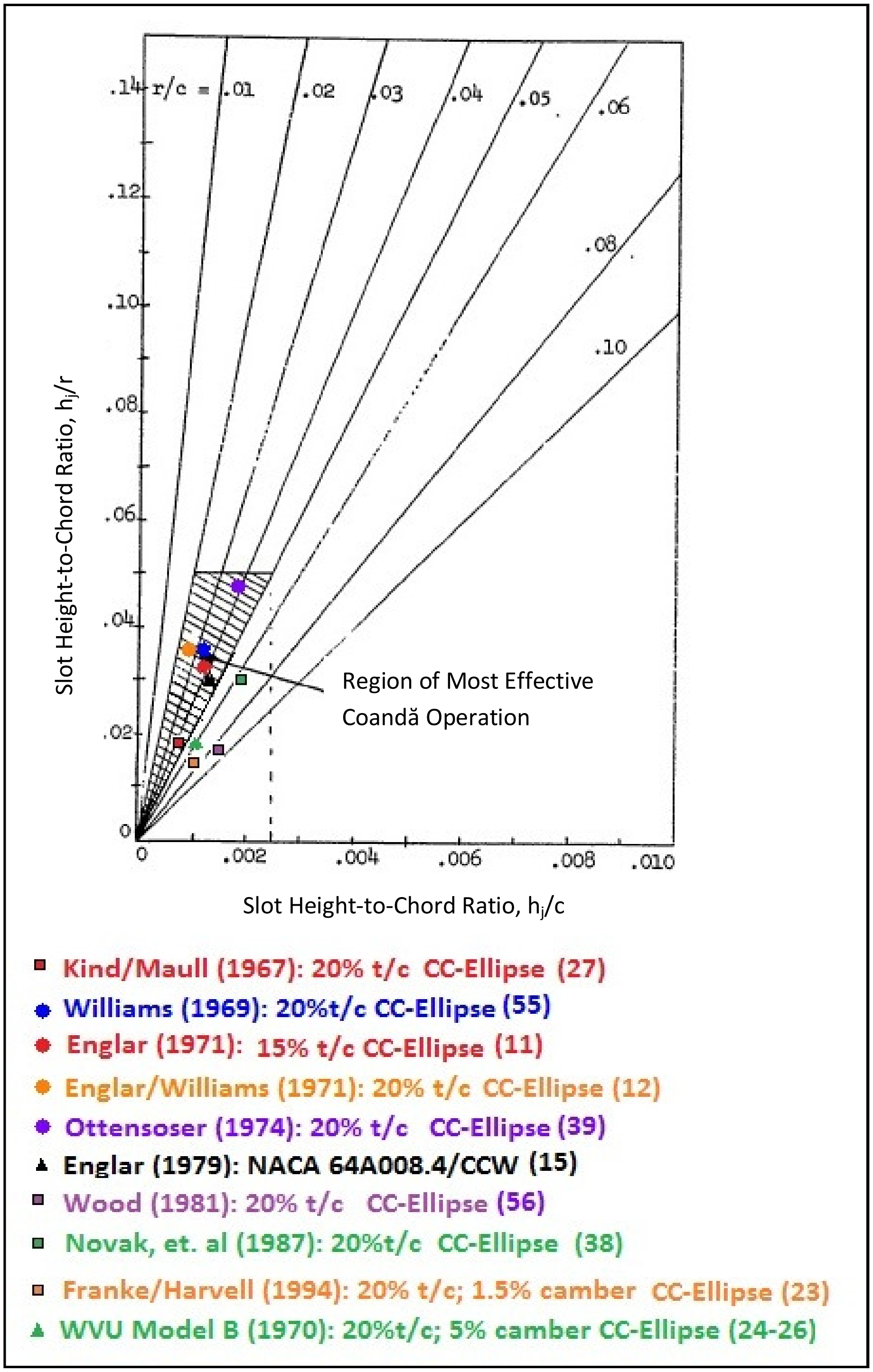

FIGURE 7. Notable Airfoils used in Past Research and their Comparison to "The Region of Most Effectiveness" [11].

It is the summary of all of the work conducted over the past five decades that will provide the future researcher with the background needed to apply what has been discovered. Several of these graphical models can be generated from the wealth of research that has been conducted.

5. CONCLUSIONS

Through the study of previous experimentation, it was possible to see the development of circulation control technology from its early years of use on fixed wing aircraft, into rotary application and hydrodynamic uses and finally to see an interest in conducting studies for use in renewable energies. A research map of the applications and the directions in which this technology has been adapted can clearly be observed in this study and a natural progression as to what research still needs to be completed to help make circulation control a viable lift enhancement device for aircraft, automobiles, hydrodynamic applications, and wind turbines. With the data collected in this study, several other baseline and design aid figures, similar to Figure 7, can be generated in order to help further the advancement of circulation control technology and ensure that this science moves toward implementation.

There is also evidence leading to the realization that CC technology has effectively expanded the range of operational conditions for such devices. Maybe the technology, or the state of the art, has finally arrived.

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