WAKE VORTEX WINTIP-TURBINE POWERED CIRCULATION CONTROL HIGH-LIFT SYSTEM

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ABSTRACT

NASA's Vehicle Systems Program is investing in aeronautics technology development across six vehicle sectors, in order to improve future air travel. These vehicle sectors include subsonic commercial transports, supersonic vehicles, Uninhabited Aerial Vehicles (UAVs), Extreme Short Takeoff and Landing (ESTOL) vehicles, Rotorcraft, and Personal Air Vehicles (PAVs). While the subsonic transport is firmly established in U.S. markets, the other vehicle sectors have not developed a sufficient technology or regulatory state to permit widespread, practical use. The PAV sector has legacy products in the General Aviation (GA) market, but currently only accounts for negligible revenue miles, sales, or market share of personal travel. In order for PAV's to ever capture a significant market, these small aircraft require technologies that permit them to be less costly, environmentally acceptable, safer, easier to operate, more efficient, and less dependent on large support infrastructures.

A synergistic technology set is proposed that would use Circulation Control (CC) trailing edge blowing coupled to a wake vortex powered wingtip-turbine air compressor. This technology would provide small aircraft with the ability to takeoff and land in shorter distances, while achieving greater efficiency at the cruise condition; or takeoff and land and equivalent speeds and distances as today with a smaller wing and higher wing loading. Circulation Control has been investigated for over 30 years and shown to be very effective in increasing the wing C_{Lmax} in tests of commercial transport and fighter aircraft vehicles. However, one of the significant penalties associated with CC systems is the power required to supply the source blowing air. Another part of this problem is that the CC mass flow required per pound of aircraft, and therefore the pneumatic power required, is proportional to the square of the takeoff velocity. Applying CC systems to aircraft that takeoff and land at relatively high speeds, such as commercial transports and fighters that are on the order of 120 knots, requires significant blowing power. Applying a CC system to GA aircraft that takeoff and land at speeds of about 60 knots, would require lower mass flows and are potentially a better fit for this technology. GA aircraft currently suffer from poor cruise efficiencies because the wing areas are sized by the takeoff and landing condition, making the wing approximately twice as large as required for efficient cruise. In addition over sizing the wing to meet takeoff and landing results in low wing loading which is much more susceptible to turbulence, resulting in poor ride quality compared to higher wing loadings. Applying a CC system to a GA aircraft would achieve a higher C_{Lmax} than current solutions, which are typically on the order of 2.0. Obviously a more sophisticated high-lift system could be applied other than simple, single element flaps; however, GA operations and pilot skills require a system that is less prone to external hanger-rash damage, inspections, and high cost manufacturing and maintenance than those used by other aircraft to achieve a higher C_{Lmax}. A CC highlift system offers the potential of a no external moving parts, and relatively few internal parts. Development of a CC system for GA aircraft would permit either reduced wing areas for takeoff and landing at equivalent airspeeds and runway lengths as today, with improved gust handling qualities, or reduced field length operation for smaller infrastructure requirements.

Utilizing a wake vortex tip-turbine as a compressor for the CC air mass flow provides a relatively failsafe method that is not coupled to the engine. In addition, the power is pulled from the wing tip vortex during the high-lift condition when the vortex strength is the greatest, and doesn't require additional power. The vehicle is however encumbered with two additional systems, a tip-turbine compressor and a pneumatic trailing edge with internal actuators. The additional weight and cost of these systems is therefore balanced against the benefits to determine if these technologies can sufficiently buy their way unto the vehicle. If a variable pitch wing tip-turbine is utilized, a reduction in cruise induced drag is possible by optimizing the blade pitch, which effectively varies the endplate loading if the blades are locked in place and not permitted to rotate. A systems study is outlined in this paper to determine quantifiable benefits of a GA-CC system, with initial investigation suggesting a potential for favorable tradeoff, although this is highly dependent on the weight and cost of the wing tip-turbine and CC system.

INTRODUCTION

Personal Air Vehicles (PAVs) are envisioned as the next logical step in the natural progression in the nation's history of disruptive transportation system innovations. As the automobile improved quality of life and standards of living in the 20th century, PAVs are envisioned to do likewise in the 21st century. PAVs are defined as self-operated aircraft, capable of use and affordable by a large portion of the general public. The goal of these vehicles is to provide a breakthrough in personal air mobility, through dramatic time-savings and increased reach, and therefore a greatly improved quality of life. There are two key questions involving the future of PAVs; first, is there a significant potential benefit developing such a capability, and second, is such a transportation system affordable and technically possible. An understanding of the current state of mobility is required prior to proposing any improvements, or understanding comparative benefits between systems.

Mobility studies[1] have shown that over the last 100 years, while travel speeds have increased ten-fold, the average amount of time traveled per day has remained relatively constant at about 1.25 hours per day. This statistic also holds true for other countries at different effective technology levels. Over the last 30 years average ground speed has increased slightly to the current value of 35 miles/hour, with 1995 and 2000 data showing the first decreases for ground mobility in many of the most productive regions of the country. Therefore the daily radius of action (or reach) has improved from about 3 miles per day in 1900, to about 25 miles per day (each way) in 2000 for intra-urban travel. While autos serve the travel market well for trips under 50 miles, and commercial transports achieve improved block speeds for trips over 500 miles; neither method provides door-to-door speeds between 50 and 500 miles that PAVs could provide. Considering that this trip distance accounts for approximately half of all trips for distances greater than 50 miles, there is the potential for a significant impact to how people travel. The objective of PAVs is to further increase the daily reach another factor of 4 to 8 times, to permit a similar expansion of society into underutilized land resources.

The vision of providing on-demand personal air mobility is tightly aligned with NASA's Aeronautical Research Theme of enhancing mobility, and providing faster, further travel, anywhere, at anytime. NASA's aeronautics blueprint defines the areas of responsibility of increasing national security, improving quality of life, and expanding economic growth. A robust aviation system, providing increased daily mobility, and a new growth market for industry products meets these goals. The key discriminator to determine if NASA should be involved is whether there is a substantial public benefit, and if NASA is the only entity capable of bringing about this benefit. The most telling answer to this question is the fact that with the many 25 year plans that exist across federal and local government planning, the focus is on trying to maintain current mobility, not provide a radical improvement.

NASA has already made investments in small aircraft through AGATE (Advanced General Aviation Transportation Experiments), GAP (General Aviation Propulsion), and SATS (Small Aircraft Transportation System) [17]. Combined, these programs have established advanced cockpit systems, crashworthiness and lightening strike standards, an advanced small turbofan engine, automatic takeoff and landing vehicle control, prototype efforts for a Highway in the Sky airspace control system, and many other elements of the total required system.

Achieving focused research objectives requires that there is a clear understanding of the vehicle class being proposed, as well as the concept of operations. PAVs would operate in the near-term from the current base of 5300+ public and 5000+ private general aviation airports[17]. Many more airfields are in use than people suspect, with a recent survey of operations showing over 18,000 airfields in use. This number excludes the nearly 10,000 additional heliports that are available, with many of these locations coincident to hospitals. PAVs would not operate out of the busiest 100 public airports, which comprises the hub and spoke system. Essentially, the infrastructure already exists today to support a distributed PAV transportation system, at least in terms of land use. Typically one of the largest hurdles in developing a radical improvement in society is the development of the new infrastructure. In the case of PAVs, the infrastructure is essentially already in place, and is simply a drastically underutilized resource.

However, the availability of existing infrastructure raises a critical issue in terms of the window of opportunity for when a PAV transportation system could be operational. One argument would be to wait until the current ground and air systems reach a level of service that requires market forces to demand a new solution. This is not realistic for two reasons. First, establishing the changes required in the airspace system will almost certainly take over 20 years, just as it took local governments 20 years from the introduction of the automobile to provide sufficient infrastructure for autos to be considered useful. Certainly local governments are not going to build the air highways, and federal implementation of a national system is required. There is the need to plan at least 20 years ahead, which puts the U.S. squarely up against the wall of 20-year congestion projections that appear unmanageable for many of the most productive regions of the country. The second reason for near-term development of an on-demand transportation system is that the required infrastructure is disappearing at a rapid rate. Currently small, public use airports are being dismantled at an averaged rate of one airport every several days as neighborhoods encroach upon rural areas, and populated regions petition them out of existence because they are viewed as irrelevant and an annoyance. These small airports provide an untapped transportation resource that will not be able to be replaced in later years.

VEHICLE CAPABILITIES AND REQUIREMENTS

The question arises, what are the mission requirement differences between PAVs of the future and current GA aircraft that are available in the market today. The future PAV on-demand market will certainly evolve from the current GA market as technologies and capabilities are developed to affect a larger market share. A shift to point-to-point operation models has already occurred with some airlines, though still only at larger airports. As the on-demand market evolves, it is likely to first exist as professionally piloted air-taxi operations from the smaller airports as an intermediate step towards personal on-demand service. As costs decrease, through such factors as lower acquisition costs and single-pilot operations, more pervasive air-taxi operations of higher utilization vehicles will establish the initial on-demand market. The self-operated on-demand market will follow with the addition of ease of use technologies that permit low cost licensing, and modern certification practices that permit manufacturers to utilize current quality assurance manufacturing processes (instead of the current quality control processes) to achieve both safer and lower cost, high quantity products. The self-operated market will likely evolve into missions that align themselves to the transportation needs of two very different mission classes, rural/regional and intra-urban travel. There will not be a single optimum configuration for these missions, but instead a spread of future potential missions and vehicles that is very broad, just as the automobile market involves from sports cars to SUVs. Therefore it is difficult to select one or two representative missions that can accurately convey the vision of their future capabilities; however representative concepts put the missions into context and provide the ability to understand the vehicle sensitivity to technology investments.

The technology challenges of providing a common place, safe, affordable, comfortable, and acceptable method of self-operated air travel are significant. This list includes developing aircraft ease of use on par with autos, involving uniform displays and controls, along with ease of pilot licensing. At the same time, these vehicles must be able to operate in near all weather capability to achieve high mission completion rates, requiring weather avoidance, and icing awareness systems, with no visibility restriction for landing. In order to provide access to many more operators, licensing and training must become far more easy, requiring a high degree of vehicle automation for systems involving self-diagnosis, pre-flight checklists, emergency procedures, and health monitoring. The combination of all these ease of use characteristics must combine into safety statistics that are on par with commercial airlines, requiring a reduction of almost ten times to the current GA accident rate. Good neighbor operations must be achieved that include noise levels that are on par to motorcycle standards, along with emissions that are equivalent to current autos. Comfort must also be significantly improved, with interior noise levels, and ride quality that are comparable to automobiles. Unless both manufacturing and operating costs are reduced dramatically, personal air travel cannot support a rational selection, even based on value of time and travel time savings for the vast majority of the public. Small aircraft major cost elements are the engine and avionics subsystems, and assembly labor; this necessitates new propulsion system solutions that are based on higher volume production such as auto engines, standardization of avionics and data transfer systems, and lean structural design concepts that can achieve drastically reduced touch labor.

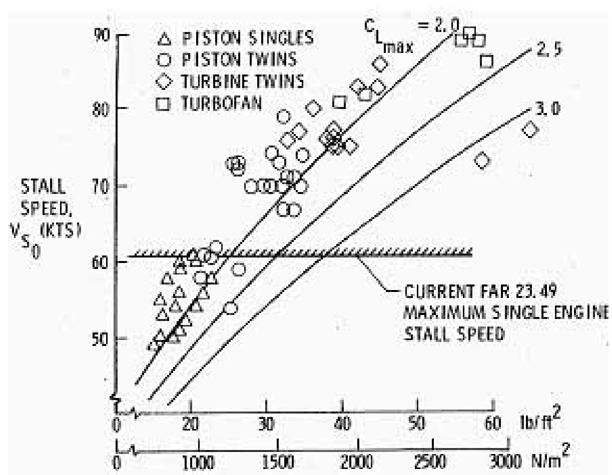

Figure 1: Stall speed of GA aircraft that results in low wing loading and relatively poor gust handling qualities.

The required capabilities that this paper focuses on are the need for improved efficiency, and reduced takeoff and landing field lengths. Currently a 4 passenger, 160 knot GA aircraft achieves about 13 miles per gallon at cruise, about the same as large SUVs. If PAVs are to be an environmentally responsible alternative mode of travel, at least a doubling of efficiency is required. Small aircraft typically achieve only a cruise L/D of about 11, while their L/D_{max} is typically 16 or higher. Obviously another alternative would be to decrease the cruise speed until the vehicle is cruising at the C_L for L/D_{max}, however, this drastically reduces the block speed benefit that is being pursued. Therefore, development of a highlift system that could provide an improvement in usable C_{Lmax} would assist towards improving the efficiency.

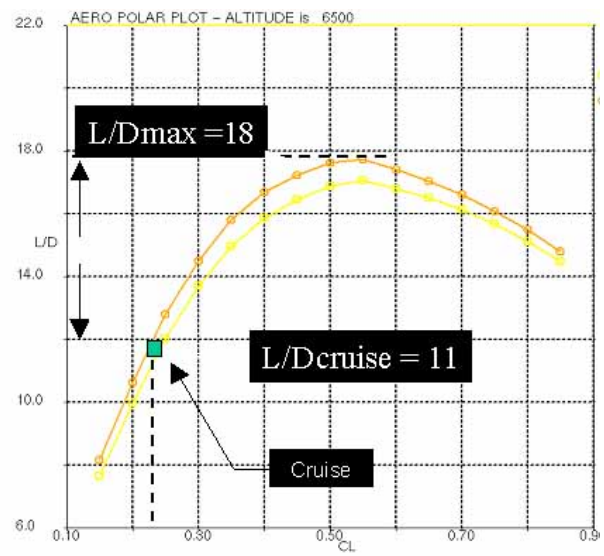

Figure 2: Drag polar of a GA aircraft similar in performance to the Cirrus SR-22, demonstrating the low cruise efficiency due to takeoff and landing wing sizing, instead of cruise wing sizing.

Achieving a C_{Lmax} of 3.75 compared to conventional GA aircraft that achieve about 2.0, would yield a 50% improvement in L/D through cruise wing sizing alone. Development of a simple, effective highlift system becomes an attractive method of achieving a substantial benefit when compared to other efficiency candidate technologies such as laminar flow, riblets, cooling drag reduction devices, retractable landing gear, etc. Alternatively, the improved C_{Lmax} can provide a reduction in the takeoff and landing field length required, and therefore the infrastructure acreage size and cost. Implicitly there is an additional safety benefit as vehicles perform Short Takeoff and Landing (STOL) operations as the effective ground speed is reduced and the potential impact speeds are decreased. However, accompanying this potential improvement in crash survivability is the increased risk of gust upset since the ratio of gust speed to vehicle speed has increased. Obviously to empower missions such as the Gridlock Commuter (Figure 4), which depend on highly accessible and widely distributed small STOLports, the infrastructure will need to be minimized.

Required Capability	SOA General Aviation	5-Years Next Gen GA	15-Years Gridlock Commuters
Ease of Use	No	Auto-like	Autonomous
Acquisition Cost ($ K)	330	75	150
Community Acceptable (dbA Flyover)	74	55	50
Emissions (HC/NOX/Lead grams/mile)	.5/1.0/.2	.05/.10/0	.03/.06/0
Reliability (accidents/100K hr)	6.5	2.0	.5
Efficiency (mpg)	13	16	28
Field Length (balanced - feet)	2500	1000	250
Block Speed (mph)	35 Auto/50 GA	100	200

Table 1: PAV Sector Capability Goals

The combination of these challenges lead to the PAV sector capabilities and goals as shown in Table 1. In order to investigate the potential technology impacts towards these goals, advanced reference concepts have been developed. Reference concepts for the 5-year, 10-year, and 15-year timeframes are shown in Figures 4 through 6, with each using a different suite of technologies to address the goals. While these vehicles concepts are not developed as a product, they do perform the valuable function of evaluating system trade-offs as a candidate technology is quantified through analysis and experimental data. The technologies listed under each of these concepts are only the initial candidate technologies that are being investigated at NASA to address the goals, many more technologies will be evaluated as they become known from other contributors. Essentially this list of capability challenges is the problem statement bounding the box of PAV technology investigations, and any proposed technology effort should be able to show significant improvements towards these goals, without causing other system penalties that negate their benefit.

The efficiency and field length goals span the entire 15-year period, and can be traded off from each other depending on the design priority. These two goals are effectively expressed by the speed range of the vehicle. The speed range is a measure of the speeds that an aircraft can effectively fly at with sufficient power and control, and is shown by the drag polar of the aircraft. The ratio of the highest achievable flight speed to the lowest is the speed range, typically on the order of 3 to 4 for most aircraft. The stall or maximum cruise speeds are not a good measure of the aircraft performance independently, because the drag polar can be shifted left or right by simply changing the wing area; however, the speed range remains the same. Thus the goal of the combination of the efficiency and field length performance goals are to maximize the speed range of the vehicle, permitting efficient flight at both the lowest and highest possible speeds.

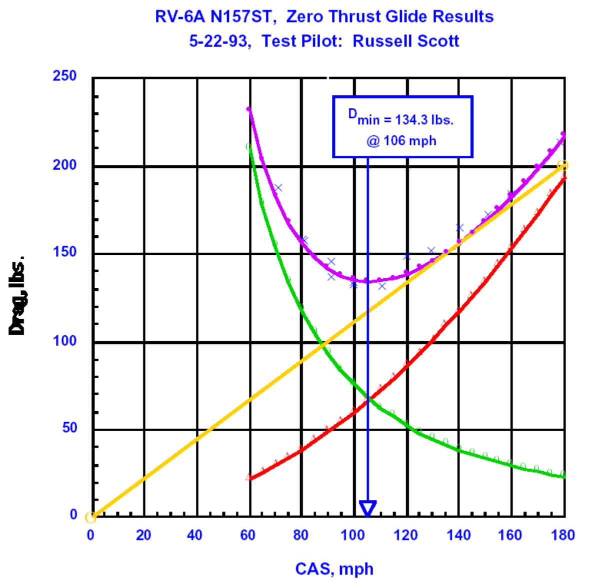

Figure 3: Drag versus airspeed graph demonstrating the effective speed range of an RV-6A 2-seat aircraft of approximately 60 to 200 mph. From CAFÉ flight test report with x indicating flight data, red line is parasite drag, green line induced drag, and the purple the combined drag polar. The yellow line intercept of the drag polar indicates Carson's speed, which is the velocity for best speed to drag ratio, or maximum speed per unit of fuel burned. The speed for the maximum L/D, or minimum power, is the lowest point on the drag polar.

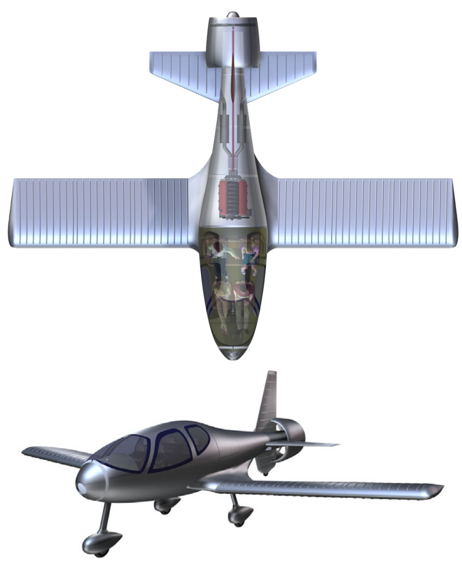

Figure 4: Near-term 5-year advanced Tailfan concept that utilizes a Haptic avionics suite, skin-stiffened low assembly labor/part count structural design, and a low tip-speed, quiet ducted propeller. This is a next generation General Aviation design for use from existing GA airports with a 2500 ft field length.

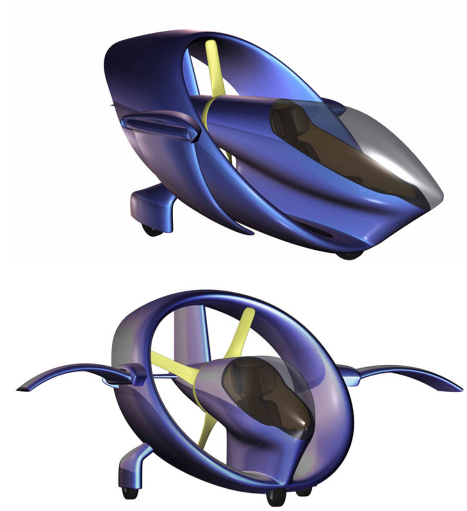

Figure 5: Mid-term 10-year advanced Spiral Duct concept that utilizes a no externally moving part deflected slipstream design based on the Custer Channel Wing and Lippisch Aerodyne to achieve a C_{Lmax} of 8-12 and achieve field lengths of approximately 250 ft. The mission for this vehicle is envisioned as a Gridlock Commuter, enabling 1 to 2 persons to travel very close to their final destination and then complete the door-to-door trip through limited speed, side-street road use.

Figure 6: Far-term 15-year advanced Tilt Nacelle Vertical Takeoff and Landing (VTOL) concept that utilizes a Multi-Gas Generator Fan propulsion system to reduce engine-out sizing penalities, and a Circulation Control Nacelle to externally expand the ducted propeller flow pneumatically to reduce the ground plane velocities and permit matching of the cruise and hover discloadings. This mission is envisioned as a Air-Taxi that accomplishes very high utilization to

amortize the significantly higher cost of achieving a VTOL aircraft.

CIRCULATION CONTROL SYSTEM

Circulation Control has been shown to be very effective in generating highlift in analysis, wind tunnel testing, and flight experiments over the past 30 years. The method of CC discussed in this paper involves blowing air from a rounded trailing edge coanda surface of the wing. This trailing edge blowing is fed from a plenum of compressed air inside the wing which is regulated with internal valves. The compressed air is typically provided by bleed from a turbine engine, or from an APU. The effectiveness of the CC system is a function of the velocity of the jet squared, therefore, to achieve the best C_{Lmax} possible, the highest jet velocities are required. Sonic jet nozzles have been shown to be substantial noise sources (a function of V_{jet}^5), and since noise is one of the primary goals of the PAV research, any CC system under investigation has been limited to less than 700 ft/s jet velocities. The same C_{Lmax} can be achieved by raising the mass flow through larger nozzle areas, however the power requirement for the compressor will rise proportionally. One of the principle reasons CC systems have not achieved transition to operational aircraft is because of the blowing power. The power required for the pneumatic system is also aggravated by the engine-out climb requirement during takeoff; this is the principle engine sizing condition so any bleed taken at this critical sizing point results in even larger engines. Recent research into CC systems have centered on unsteady or pulsed blowing since this has the potential to reduce the mass flow required by up to one half while achieving the same C_{Lmax}.

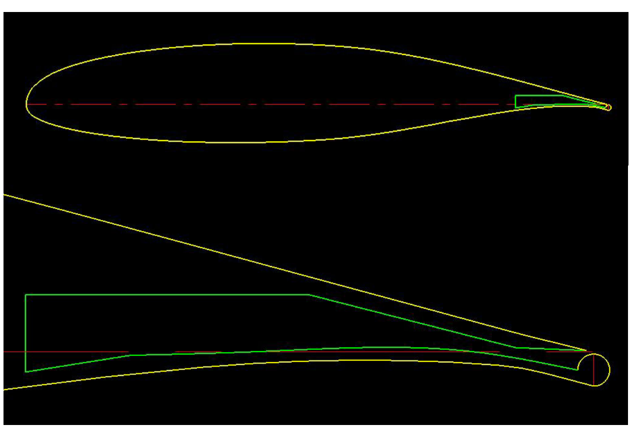

Figure 7: A GA airfoil section with a Circulation Control plenum and trailing edge.

The CC wing concept involves a jet of high-speed air blown over a circular or semi-circular trailing edge that, due to the Coanda effect, clings to the trailing edge. This allows active control of the stagnation points and, consequently, control over the circulation of the wing. A 17% supercritical airfoil designed for circulation control is shown in figure 7. The shape of the super critical airfoil section is very close to that of the GAW-1. With this type of CC airfoil, it is possible to achieve a C_{Lmax} of 5 to 6 with sonic flow. Using data from reference 2, an approximate 3-D drag polar for a GA aircraft was developed over the full range of C_μ. C_μ is the measure of merit, defined as the mass flow rate multiplied by the jet velocity at the slot divided by the multiplication of the dynamic pressure and the reference wing area, or:

$$C_\mu = \frac{\dot{m}V_j}{qS_{ref}}$$

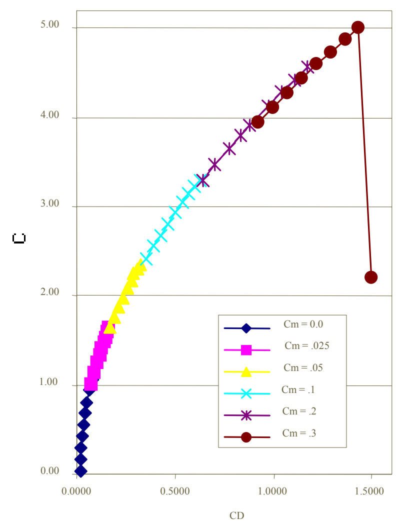

Figure 8: 3-D Drag Polar of a GA-CC Wing System

The wing system is assumed to have full span blowing from the fuselage to the tip, thus necessitating spoilers as roll control surfaces. One of the system impacts of utilizing a CC system, or any high performance highlift system, is the need for additional tail surfaces to trim the larger pitching moments, resulting in lower performance of the 3D system when compared to 2D wind tunnel results.

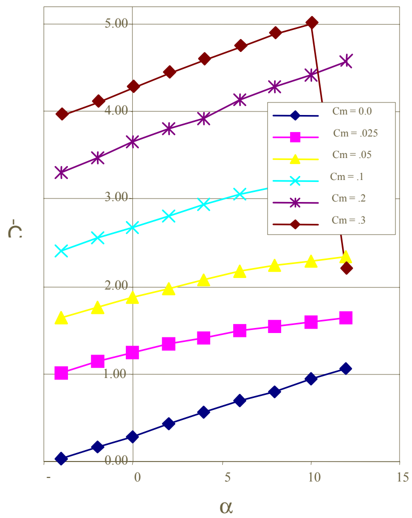

Figure 9: 3-D Lift Curve Slopes of a GA-CC Wing System

Initially an engine turbocharger was investigated for the supply of compressed air for the CC highlift system. This arrangement appeared to have promise since aircraft turbocharging is only used for altitude compensation, and not for increasing power at takeoff. Therefore, with the pressurized turbocharger air going out the wastegate at takeoff and landing, 100% of the turbocharger air mass flow is available for bleed to the CC system. However, use of the turbocharger as the air source is complicated by the problem of engine failure and the need to still achieve the same highlift with or without the engine running. A slow burn rocket gas generator was investigated as a backup system since only a limited 1 to 2 minute air plenum supply would suffice for an emergency landing flare while still achieving the CC system highlift performance during the approach. However, this added complexity plus the need for the engine to remain at high power during landing to supply the air while decelerating under normal conditions would impose an additional thrust reversing system. As the complexity of such a system continued to rise, alternate methods of providing an air source that were not dependent on the propulsion system were investigated.

In prior CC application studies, it has been argued that since the CC blowing results in a thrust component (since the air mass is injected at the trailing edge), using bleed air does not result in a thrust loss. However, this is not accurate since the bleed air is pulled prior to use in a combustion process, so that pulling 1 hp of bleed air results in robbing many times that power amount from the engine. In addition, the amount of thrust generated from a small, high-speed jet area is considerably less than the thrust generated by an equal amount of power put into a lower speed flow in a larger area. This is especially true for small propeller aircraft that takeoff and land at low speed; this can easily be visualized by looking at a curve of horsepower required versus thrust discloading, with a typical propeller providing about 6 lbs of thrust per hp, while a high speed jet nozzle providing less than 2 lbs of thrust per hp. The key problem remains however, that the CC system power must be provided at the propulsion sizing critical condition of low-speed engine failure, so that any blowing power extraction is magnified by the ratio of total power to engine-out power. Clearly CC systems will have a difficult time buying their way unto an aircraft system when propulsion system scaling is required.

WAKE VORTEX WINGTIP TURBINE SYSTEM

An ideal source of air for a CC system would provide a pressurized air source without power required during the takeoff and landing phases of flight, while providing some additional benefit during the other phases of flight to cover the additional CC system cost and weight. A wake vortex wingtip turbine system offers exactly this potential.

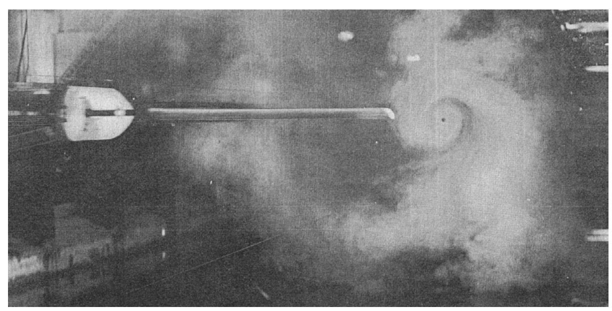

Figure 10: A wing tip vortex demonstrated in forward airspeed wind tunnel tests.

As shown in Figure 10, vortices are shed when any change in lift occurs along a wing span. These vortices roll up where the vortices are strongest, which is at the tip location where the lift becomes zero. The resulting rolled-up core vortex has energy associated with it, which is equivalent to the induced drag of the vehicle. Returning to Figure 3, it can be seen that the induced drag, or vortex energy, is greatest at the lowest speed when the vehicle is flying at the highest C_L, which is at the takeoff and landing portion of flight. Therefore the vortex velocity component is a maximum at the condition where we need to extract the most energy for a CC compressed air source. Figure 11 shows a representation of a wingtip turbine and the velocity components that provide power to the turbine blades; namely that there is a vortex velocity component, and a free stream velocity component, and the resulting velocity component is the vector sum of the two. Again, the easiest way to visualize the magnitude of the resulting velocity vector, which is directly proportional to the vortex energy available to use for turbine work, is to look at the total drag at any given vehicle flight speed as in Figure 3.

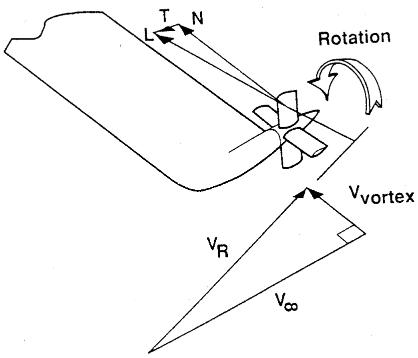

Figure 11: A wingtip vortex turbine system and the velocity components seen by the blades.

Prior research has been conducted on wake vortex wingtip turbines at NASA in the 1980's. However, the focus of this research activity was to provide an APU-like energy source for transport aircraft during cruise to increase efficiency. Analysis, wind tunnel, and flight test investigations resulted which demonstrated that the vortex turbine could successfully remove energy from the vortex and free stream velocities. The flight tests were conducted on a GA aircraft not because this was the intended application vehicle class, but because this was the lowest cost practical testing method. Figure 12 shows of a picture of the modified Piper Arrow GA aircraft in flight with the tip turbines active, and a close-up of the turbines blades after conducting oil flow visualization tests. The oil flow on the wingtip pod in front of the blades clearly shows the vertical flow direction, even at the efficient cruise condition. All analysis and flight test data was performed at the efficient cruise condition, since this was the area of application for the study. However, this speed point also corresponds to the weakest energy state of the vortex turbine, so only marginal amounts of power were shown. Figure 13 shows the amount of horsepower extracted from the 4 bladed system at various blade angle settings, but only at the 122 knot flight speed. The twist distribution was also not ideal, but simply a first principles approximation of an elliptical load distribution across the blade at one flight speed. The turbine blades for this test were fixed, but ground adjustable for simplicity of manufacture, though this resulted in each data point along the Figure 13 curve being a different flight test. While valuable research, the prior effort into vortex wingtip turbines offers only a glimpse of the required data for application to the power source of a CC system.

Figure 12: Piper Arrow GA aircraft modified with a wingtip turbine system in 1988 to investigate the potential for extracting power during cruise for replacement or elimination of APUs and improved cruise efficiency.

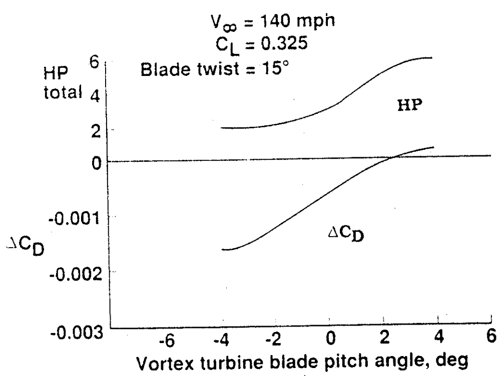

Figure 13: Horsepower extracted or drag reduction versus the blade pitch angle setting, demonstrated from cruise speed flight tests of a GA aircraft wingtip turbine system. Additional power extraction was possible, but no testing was performed of blade angles involving an increase in the vehicle drag since the investigation was for cruise drag applications.

As mentioned previously, a desirable attribute of a CC power source is that it also serves some purpose during the other phases of the mission besides at takeoff and landing. Figure 13 shows that depending on the blade angle, a vortex turbine can be used to either extract power, or provide a reduction in the induced drag. To derive the maximum benefit both for the CC air source power and cruise drag reduction, a variable pitch system would be required to vary the turbine blades. For each of these blade angles, a different turbine rpm results, with optimum power extraction occurring at approximately 400 rpm. The induced drag is reduced as the rpm is decreased, with the minimum induced drag occurring with the blades fixed in a stationary position acting effectively as wing endplates.

A first principles sizing effort was performed to see if a vortex wingtip turbine has sufficient energy to power a CC system. A full span blowing system was sized to yield a 30 ft trailing edge nozzle with a height of .06 inches. A constraint of Mach .70 was imposed on the CC blowing jet for noise reasons, yielding a plenum pressure of 20 psi, or a 1.4 pressure ratio. The CC system provided an improved lift curve slope as shown in Figure 8 and 9 previously, with the mass flow required at a C_{mu} of .20 being approximately 9.2 lbm/sec. This system yields a 3-D C_{Lmax} of about 4.0, yielding a $C_{Llanding}$ of about 2.6 and $C_{Ltakeoff}$ of 2.1 when stall margins are taken into account. The net effect on the vehicle is a reduction in wing area from 174 to 104 square feet, and an improvement in L/Dcruise from 11.8 to 15.1. However, the power required to drive the CC system with a 75% efficient compressor is about 40 hp per side at the peak condition to achieve a CLmax of 4.0. While this amount of blowing would not be used (due to the stall margin), it does raise the interesting dilemma that in order to maintain a sufficient stall margin the sizing condition for the CC system needs to have a significant excess capacity. In order to maintain a stall margin of 1.3, the CC system would require the ability to quickly vary the C_{mu}, thus imposing a gust allevation/stall response time on the CC system in order to be certifiable. Looking at Figure 9 it can be seen that it is not possible to achieve an adequate stall margin at a constant C_{mu} unless the approach angle of attack is very low, for this example -10 degrees at landing!

The question remains whether there is sufficient energy in the vortex flow to power a CC system. A less agressive CLmax could have been selected to achieve a lower mass flow requirement. Also, the mass flow estimate is artificially high due to the assumption of a constant thickness slot and constant spanwise blowing. Tayloring of the spanwise blowing to achieve a minimum induced drag would reduce the mass flow at outboard wing sections. Increased turbine power could be extracted by increasing the blade diameter and number of blades. While it is possible to extract this amount of energy from the wingtip vortex, it will be a significant challenge to do so with a compact system that can permit use near ground proximity, and with a lightweight turbine system. An estimate was performed of the weight of a CC wake vortex system, with the results indicating a 130 lbs total system weight (which is about half the weight of the wing), distributed over the following weights per side: 30 lbs centrifugal compressor, 12 lbs gear reduction from 40,000 rpm to 400 rpm, 8 lbs 4 bladed 3.5 ft diameter turbine, 5 lbs housing, and 10 lbs in internal valving and ducting. From a mission and sizing perspective, for this GA application effort, there was a net savings in fuel weight of 77 lbs from the baseline of 404 lbs. In addition the wing weight was reduced by a marginal 8 lbs from the 276 baseline wing weight. The reason the wing weight reduction is so low, considering the wing area was reduced by 40%, is that the reduction in wing skin weight is taken up by increased wing spar weight due to the decreased thickness of the beam. This is a result of the chord decreasing and keeping a constant thickness to chord ratio of the airfoil. Obviously the ability to go to thickness sections would permit an additional benefit, if the circulation control system also had some method of achieving a boundary control system to avoid separation due to the increased thickness. So, from a first principles analysis, a CC vortex turbine system sized for equivalent takeoff field length, but with a smaller wing, yields a slightly heavier aircraft. However, a more detailed analysis, and the incorporation of alternate integration schemes or blowing systems (such as pulsed blowing to reduce the mass flow) could dramatically change this result. In order to really understand the potential of such a system, a detailed system study needs to be performed.

PROPOSED SYSTEM STUDY

While the first principles study was useful for determination of application potential, a much higher-order analysis is required to make a determination of the exact performance differences. It is proposed that the following study is conducted to develop a more complete understanding of this synergistic technology suite, and justify scale or flight testing.

1) Perform a wake vortex energy balance for a determination of vortex energy available, and the required capture area and turbine/compressor efficiencies.
2) Vortex lattice static blade force and torque modeling and analysis in proximity to wing for a determination of turbine loads at the takeoff and landing condtions.
3) Transient takeoff time step analysis to show sufficient takeoff power and turbine blowing availability, as well as the CC/Tip-turbine responsiveness at landing at an assumed maximum gust response condition.
4) Wingtip-turbine number of blade, diameter, chord, twist, taper, axial location optimization for maximum power extraction and minimum cruise drag.
5) Sensitivity studies of a cruise-sized wing, varying the C_{mu}, C_{Lmax}, and coompressor power available.
6) Optimization of the wing aspect ratio and CC system in combination, incorporating the vortex blade endplate effectiveness at cruise.
7) A detailed CC system weight and cost estimation with feedback into aircraft system in order to yield a cost to benefit ratio.
8) Estimation of the wake vortex dissipation with vortex energy removal for highlift to understand if this is another potential benefit as this type of system is applied to very large span constrained transports that cause significant takeoff and landing vortex hazards that yield operations timing delays.
9) Investigation of turbine failure modes (ie locking in non-optimum positions) to determine system robustness.
10) A repeat of steps 5 and 6 for a STOL wing application.

SUMMARY

The use of Circulation Control and a Wake Vortex Tip-Turbine are suggested for investigation in order to provide a simple, effective highlift system for General Aviation aircraft. This synergistic use technologies offer the potential to achieve on the order of a 50% increase in cruise efficiency, or a reduction in field length for STOL performance. A first principles assessment of considerations has been laid out in this paper, along with the steps required in order to conduct a complete system study. Initial results suggest that use of a wake vortex wing-tip turbine could provide sufficient power for a modest CC system that could achieve a C_{Lmax} on the order of 3.5. However, prior test results of a wingtip turbine was extrapolated from cruise data points to the landing condition and therefore deserves significantly more systems investigation prior to large-scale testing. This use of a wingtip turbine provides a unique method of providing an air source for a CC system that is not associated with the vehicle propulsion system. In addition the tip turbine may be locked in place during cruise, when compressed air is not required, to provide an endplate effect, and therefore a reduction in induced drag. While the combination of these systems could provide a relatively simple highlift system that is fault tolerant, it does have the possibility of adding on the order of 130 lbs of weight to the wing, which is less than the 85 lbs of fuel and wing weight savings due to reduced wing area and the improvement in efficiency. Therefore, a GA aircraft with a CC and tip-turbine system would be somewhat heavier than a conventional GA aircraft, thus reducing some of the efficiency improvement. It is suggested that an in-depth system study be conducted to determine improved estimates of the CC and tip-turbine systems, including higher-order analysis at the landing condition, and that a full systems analysis of the concept be completed.

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EQuiPT Vehicle Technology Capabilities

On-Demand Access to 10,000 airports in the near-term, with point-to-point community accessibility in the long-term; providing reduced travel times compared to auto and airlines for ranges of 25 to 500 miles.

Required Capability	SOA General Aviation	5-Years Next Gen GA	15-Years Gridlock Commuters
Ease of Use	No	Auto-like	Autonomous
Acquisition Cost ($ K)	330	75	150
Community Acceptable (dbA Flyover)	74	55	50
Emissions (HC/NOX/Lead grams/mile)	.5/1.0/.2	.05/.10/0	.03/.06/0
Reliability (accidents/100Khr)	6.5	2.0	.5
Efficiency (mpg)	13	16	28
Field Length (balanced - feet)	2500	1000	250
Block Speed (mph)	35 Auto/50 GA	100	200

Mission: Range = 500 miles, Payload = 4 passengers, Gross Weight ~3500 lbs, IFR capable

FY04 FY09 FY14 FY19

EQuiPT Efficiency Technologies

Initially a 20% improvement in sfc is achieved by utilizing automotive engine technologies

- Near-term elimination of 100LL fuel; replaced with slightly reformulated auto grade fuel
- Auto engines have higher compression ratios, digital control, improved combustion, etc…
- Auto engines are potentially certifiable with complete airframe/propulsion redesign (with a slight weight penalty but huge cost reduction), but are not retrofitable to existing airframe/propulsion

An additional 50 to 60% improvement in mpg is required to achieve automobile efficiency levels

- Engine technologies can offer an additional 20% reduction in sfc (with a weight penalty)
- Small aircraft currently achieve cruise L/D's of 10 to 12, although they have L/D_{max}'s of 16 to 18
- Combination of FAR Part 23 low takeoff and landing speeds (achieving 2500' field length operation and operational safety) and relatively low cruise altitudes result in wing sizing that is 3 times larger than cruise sizing ($C_{Lcruise}$ of .18 vs .54)
- Current small aircraft achieve a C_{Lmax} of 2 to 2.2, and personal use will continue to require simple highlift systems that are not complex or expensive, maintenance prone, or hanger-rash vulnerable.
- Achieving a simple, effective highlift system could yield a 60 to 80% improvement in aero efficiency.

VEHICLE SYSTEMS Where Innovation Soars
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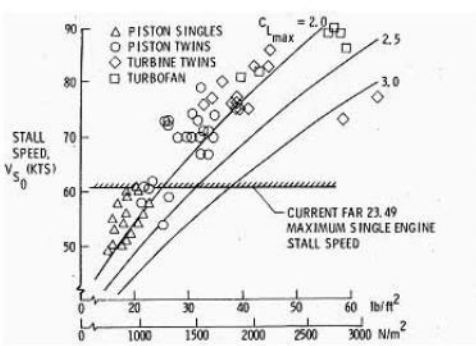
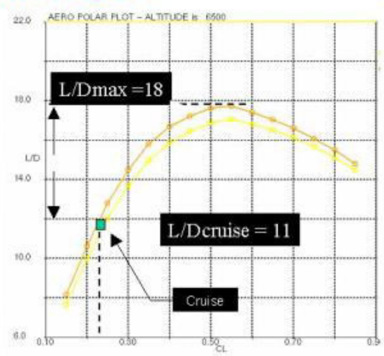
EQuiPT Aero Efficiency Technologies





FAR Part 23 requires a stall speed of 61 knots, resulting in low wing loading and relatively low takeoff and landing speeds.

Higher wing loading would provide improved ride quality.
(lower gust and cross-wind sensitivity)

Small aircraft have significantly oversized wings for cruise, with a 60% increase in L/D possible with a cruise-sized wing.

Re-sizing the wing with a C_{Lmax} =4.0 yields an $L/D_{max} \sim 20$.
(assuming no additional drag ie blunt TE)

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EQuiPT Short Takeoff/Landing Technologies

In the near-term a 1000' field length enables reduced approach speeds for improved safety and reduced community noise signatures

- The ultimate objective in reducing the balanced field length is to reduce the infrastructure investment and runway protection zone required for highly distributed airfields.
- Safety (in terms of accident avoidance reaction time and survivability) is proportional to the approach speed (if equivalent control margins and gust sensitivity can be achieved).
- Takeoff and approach community noise footprint can be reduced through field length reduction.
- However, a 1000' field is not significant enough of a reduction to justify a new infrastructure, but it does permit an evolution in capability towards the 250' long-term objective.

The long-term 250' field length is a near VTOL capability that enables point-to-point.

- Permits highly distributed, community-based point-to-point operation with maximum potential block speed, productivity, and mobility.
- Vehicles become cross-wind insensitive due to 100' roll distances and omni-directional landing.
- Powered-lift systems are required, with high T/W and engine-out tolerance, but not nearly the penalties of a hoverable VTOL (typically VTOL capable aircraft are operated this way for overload).

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Circulation Control (CC) Application

CC provides maximum effectiveness for small aircraft

- CC effectiveness is based on $(Vjet/Vinf)^2$ velocity ratio, yielding either greater effectiveness or reduced mass flow given the same lift requirement.
- A Boeing 737 has an approach and rotation speed of approximately 135 knots, while a Cessna 182 is only about 65 knots, yielding a 4 x improvement in effectiveness
- A CC highlift system is potentially relatively simple, with no external moving parts.
- CC could be used to solve either the efficiency or short field problem, or possibly both through integration with additional technologies (combining higher altitutude cruise, gust alleviation, limited powered-lift, etc.)

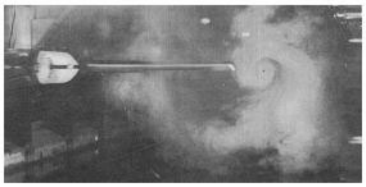
Low penalty integrated air source possible for small aircraft

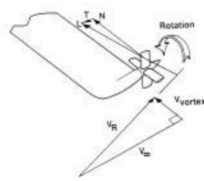
- High performance small aircraft are turbocharged for altitude compensation, not increased power at takeoff, so that considerable compressed air is thrown out the wastegate at takeoff (2 lbm/sec)
- However, linking the highlift system is to the propulsion system is problematic since the same field length performance must be achievable after engine failure, and the need for high power approaches.
- An emergency air source backup is possible (ie slow-burn, solid gas generator for 1-2 min), however it adds unwanted complexity and only single pass approaches.
- Another alternative is using the wake vortex energy to power a wingtip-turbine.

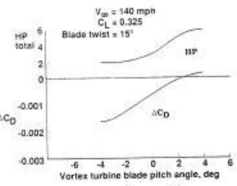
Vortex Wingtip-Turbine Application

Wake vortex could provide energy for air source

- Rotational velocity source that is proportional to the C_L, providing more energy at highlift conditions.
- Independent of propulsion; auto-gyro like in terms of engine-out and safety.
- Wingtip-turbine can provide either energy source or induced drag reduction.

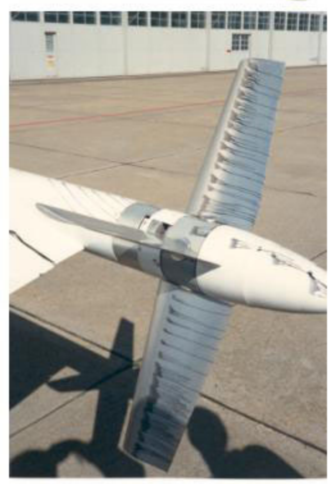






Experimentation already performed on small aircraft

- Flight validation experiment in 1988 on a Piper to verify cruise power extraction and drag reduction, (research was directed at use as cruise APU power substitute).
- Ability to extract 6 hp at cruise with no drag increase, or a reduction of 16 drag counts with 2 hp power extraction, while reducing the vortex strength.
- If increased drag is acceptable (such as at landing), there was the potential to extract 20-40 hp at low speed flight conditions.

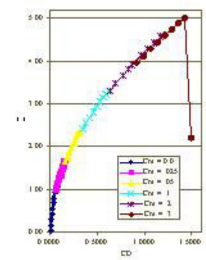


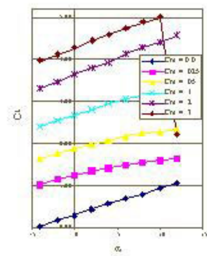
Wingtip Turbine Wake Vortex Experiment, Paterson et al, 1988, NASA Langley

Baseline EQuiPT CC System

Baseline CC system (limit turbine power, close to cruise-sized wing)

- Constant wing span, $span_{with\ blowing}$ = 30 ft, s_{ref} = 104/174 ft^2, $height_{slot}$ = .06 in
- Cmu = .2, P_{plenum} = 20.25 (1.39 pressure ratio), m_{dot} = 9.18 lbm/sec, M_{inf} = .09, M_{jet} = .70,
- $C_{Lmax\ landing}$ = 4.0, $C_{Llanding}$ = 2.6, $C_{Lmax\ takeoff}$ = 3.0, $C_{Ltakeoff}$ = 2.1
- $L/D_{baseline\ avg}$ = 11.8, $L/D_{cruise\text{-}sized\ avg}$ = 15.1
- $Power_{Landing}$ ~ 40 hp required per side peak, not operationally (with 75% $comp_{eff}$)
- 30 lb (40K rpm centrifugal compressor)
- 12 lb (100:1 gearbox)
- 8 lb (4 bladed, 400 rpm, 3.5' turbine)
- 5 lb (housing)
- 10 lb (valving and ducting)
- 65 lb CC system weight per side
- 77 lbs mission fuel savings / 404 lbs
- 8 lbs / 276 lbs wing weight savings
- Initial starting point, non optimal solution
- Variable pitch required to achieve both highlift air source and cruise induced drag reduction





Conclusions

Only initial results from system study are present and premature to determine system merits; considerable additional effort is ongoing

- Wake vortex energy balance
- Vortex lattice static blade force and torque modeling in proximity to wing
- Transient takeoff time step analysis to show takeoff power availability, CC/Tip-turbine responsiveness at landing
- Wingtip-turbine number of blade, diameter, chord, twist, taper, axial location optimization for maximum power extraction and minimum cruise drag
- Cruise-sized wing Cmu, Clmax, Compressor power sensitivity studies
- Optimization of wing AR and CC system combined
- Detailed CC system weight and cost estimation with feedback into aircraft system and cost to benefit
- Estimation of wake vortex dissipation with vortex energy removal for highlift
- Investigation into turbine failure modes (ie locking in non-optimum positions)
- Repeat for Short field CC system sizing and extropolate into 737 transport class

Geometry problems are present: rpm mismatch, compressor diameter, area reduction causes spar depth decrease, blade locking and variability for cruise

Use for short field performance is more likely than to achieve cruise-sized wing

THE USE OF CIRCULATION CONTROL FOR FLIGHT CONTROL

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Abstract

An experimental investigation into the application of circulation control on a 50° swept delta wing has been performed in a closed return wind tunnel at 25m/s. This was then extended to a sting-mounted circulation control demonstrator with two control surfaces, in order to determine whether the technique could be use for roll control whilst maintaining high lift coefficients within the limits of pitch trim. A lift augmentation of approximately 20 was achieved with all configurations. Roll of the aircraft was possible with differential blowing of the circulation control systems.

Nomenclature

b	span
$\bar{\bar{c}}$	Mean aerodynamic chord (m)
c_o	Chord (m)
C_D	Drag coefficient
C_L	Lift coefficient

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C_m Pitching coefficient

C_p Pressure coefficient, $(p-p_\infty)/q_\infty$

C_μ Blowing coefficient

$\left(\frac{\partial C_L}{\partial C_\mu}\right)$ Lift augmentation

h Slot height (mm)

$\dot{m}$ Jet mass flow rate (kg/s)

M Jet Mach number

p Static pressure on aerofoil (Pa)

p_p Pressure inside plenum (Pa)

p_∞ Ambient static pressure (Pa)

q_∞ Freestream dynamic pressure (Pa)

r Trailing edge radius (mm)

s Semi-span (mm)

S Wing reference area (m)

V_J Jet blowing velocity (m/s)

α Angle of attack (degrees)

1. Introduction

Circulation control has been recognised as a technique by which very high lift coefficients can be achieved. It exploits the Coanda effect by blowing a high velocity jet over a curved surface, usually a rounded or near-rounded trailing edge, causing the rear stagnation point to move. In turn, the upper surface boundary layer is energised, resulting in a delay in separation. As the circulation for the entire wing is modified, there is an increase in overall lift, often much greater when compared to more conventional mechanical lift devices.

Earlier research[1,2] has mainly concentrated on two-dimensional unswept wings, where the flow is predominantly attached to the airfoil. However, in this work the performance benefits of the application of circulation control for delta wings, with massive regions of separated flow, were investigated. Although more recent work[3] uses pulsed jets in a bid to reduce the total jet mass flow rate required, a steady jet was used in this investigation for model simplicity. With a system with few or no moving parts, the Circulation Control Wing (CCW) has provided considerable interest, as it is mechanically simpler, and therefore cheaper to manufacture, and less prone to mechanical failure in comparison with conventional high lift devices. Also, lift increments can be similar to those with conventional high lift control surfaces, but pitch increments can be lower, leading to improved aircraft control.

The initial aim of the study was to investigate the effect of various trailing edge configurations with a view to eliminate the cruise drag penalty attributed to large trailing edges, whilst still obtaining high lift augmentation. This was then extended to an investigation into the interaction of two circulation surfaces on a delta-wing planform with trailing edge sweep to determine whether there would be an interaction between the two jets and also whether circulation control could be used for roll control, within the limits of pitch trim and maintaining previous lift augmentation.

2. Experimental Procedure 1

The model used for the preliminary studies[4] is shown in figure 1. The CCW consisted of a generic delta wing leading edge section and a plenum/trailing edge section. The leading edge section comprised of a sharp leading edge profile with a 50° sweep, incorporating strengthening sections to reduce flexing when under aerodynamic load. The trailing edge consisted of a 6mm diameter brass rod, giving a trailing edge radius to mean aerodynamic chord ratio of $0.005\bar{\bar{c}}$, over which a narrow convergent slot provided the jet blowing A series of push-pull screws allowed the slot height to be adjusted to 0.15mm and to 0.3mm ($0.00025\bar{\bar{c}} \leq h \leq 0.0005\bar{\bar{c}}$).

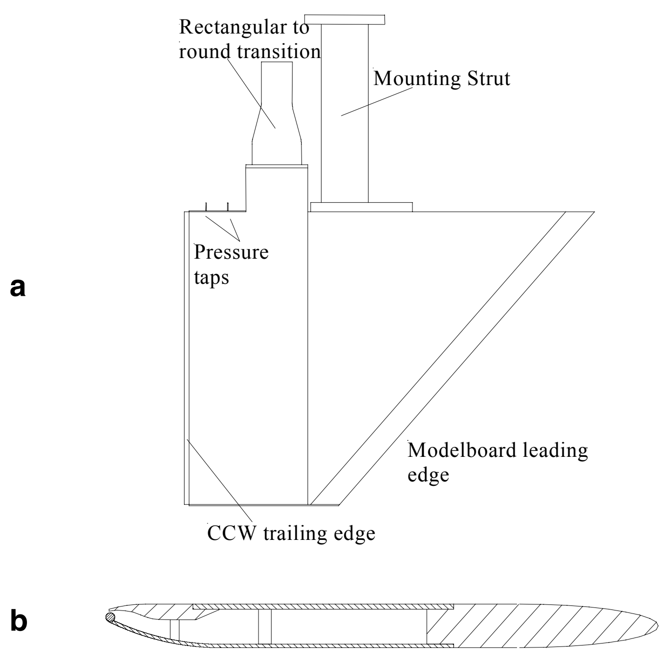

Figure 1: Model Geometry

(a). Upper surface view (b). Cross-sectional view

The model was mounted from the overhead balance in the Avro 2.74m x 2.13m (9' x 7') wind tunnel at the Goldstein Laboratory, Manchester, U.K., as shown in figure 2. A splitter board was mounted to ensure that the wind tunnel boundary layer did not interfere with measurements and the Coanda jet. Force and moment data was measured using the 6-component balance. The freestream velocity was set at 25m/s, corresponding to a freestream Reynolds number of approximately 8.5 x 10^5, and maximum jet velocities were approximately 180m/s.

The air supply was from pressurised receiver tanks fed by an Atlas-Copco compressor, delivered to the plenum by a flexible hoses, such that tare effects out of the plane of measurement were avoided. The mass flow rate was determined using an orifice plate rig and pressure and flow temperature data was transferred to the computer via an A-to-D card.

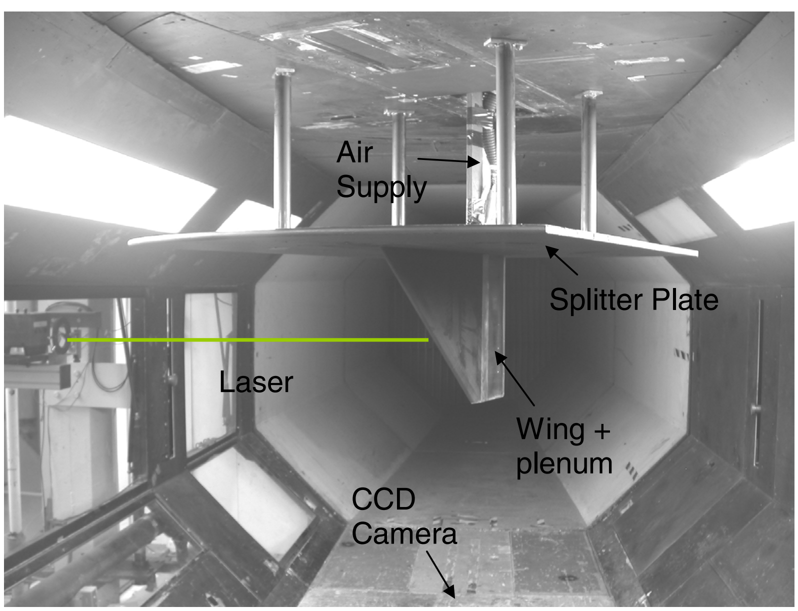

Figure 2: Model mounted in wind tunnel

A computer program was written to accumulate data and calculate the flow rate. From this the blowing momentum coefficient, C_μ, could be calculated. This was calculated using,

$$C_\mu = \frac{V_J \dot{m}}{qS},$$

where V_J is the velocity of the Coanda Jet, $\dot{m}$ is the jet mass flow rate, q is the freestream dynamic pressure and S is the model surface area. The jet velocity was calculated using the isentropic pressure distribution,

$$\frac{p_p}{p_\infty} = \left(1 + \frac{M^2}{5}\right)^{\frac{7}{2}},$$

to avoid errors that can occur using the jet area as a variable. As interest was at the low blowing rates, data was recorded at increments of C_μ of 0.0005 up to 0.01 and then using increments of 0.005 up to 0.03 to obtain general force or moment curves.

Particle Image Velocimetry (PIV) was also performed to obtain more information on the interaction of the jet with the freestream flow[5]. A horizontal lightsheet was fired at the trailing edge of the CCW and a CCD camera, positioned under the wind tunnel floor, captured pairs of images of the seeded freestream flow over the wing, as shown in figure 2. These were then analysed using TSI Insight and Tecplot 9 software to obtain velocity and vorticity data.

As part of a joint project, BAE Systems[6] calculated CFD data to compare with the experimental data.

3. Results 1

The results given in figure 5 show the effect of circulation control on the lift characteristics with a variation in slot height. There is an increase in lift with an increase in blowing coefficient, C_μ, although the greatest lift increments were found at lower blowing rates. The level of lift augmentation $\left(\partial C_L / \partial C_\mu\right)$ is of the order of 10-20. Also, it was found that the smaller slot height yields a stronger lift augmentation at smaller values of C_μ. It is anticipated, though, that a minimum slot height will be reached, where the jet no longer attaches to the Coanda surface. This requires further research.

The drag coefficient was also found to increase as the blowing rate is increased although the drag augmentation is significantly less than the equivalent value for lift, suggesting an overall increase in L/D. However, drag measurements are not presented in this paper due to an inconsistency in the data, which may be due to fluctuations in the Coanda jet or the accuracy range of the balance.

Figure 6 shows the calculated velocity vectors obtained using PIV in the form of a contour plot using the TSI Insight and Tecplot softwares. It can be seen that the external flow visibly changes at higher blowing rates, indicated by a downward deflection of the velocity vectors. The data also demonstrates the downstream extent of the wake was reduced. Due to restrictions with apparatus it was not possible to seed the jet and investigate the interaction with the freestream flow.

4. Experimental Procedure 2

A full span model was designed and constructed at the Goldstein Laboratory, Manchester, to investigate any interaction of the Coanda jets and examine the possibility of roll control, as well as lift enhancement (figure 3).

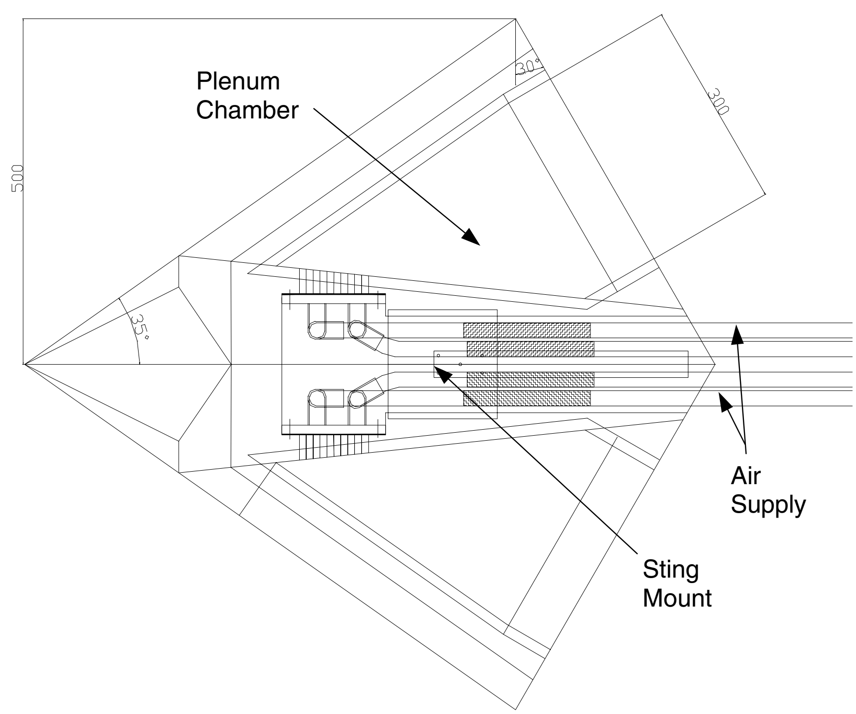

Figure 3: Schematic of full span model

The main body was constructed using modelboard, with the fuselage made from aluminium sheet. The plenum sections, made from aluminium for the upper surface and brass for the lower surface, incorporated similar trailing edge dimensions as the previous model: trailing edge diameter of 6mm and slot height adjustment from 0.05mm to 0.30mm (this was set at 0.15mm to compare with previous results). The blowing rate was again controlled using an orifice plate rig for each plenum, such that the plenum sections could be controlled independently. The air supply was controlled by the use of two valves for each plenum, allowing finer and more accurate control.

The model was mounted on a sting in the 9' x 7' wind tunnel as shown in figure 4, incorporating an internal 6-component strain-gauge sting balance to measure forces and moments.

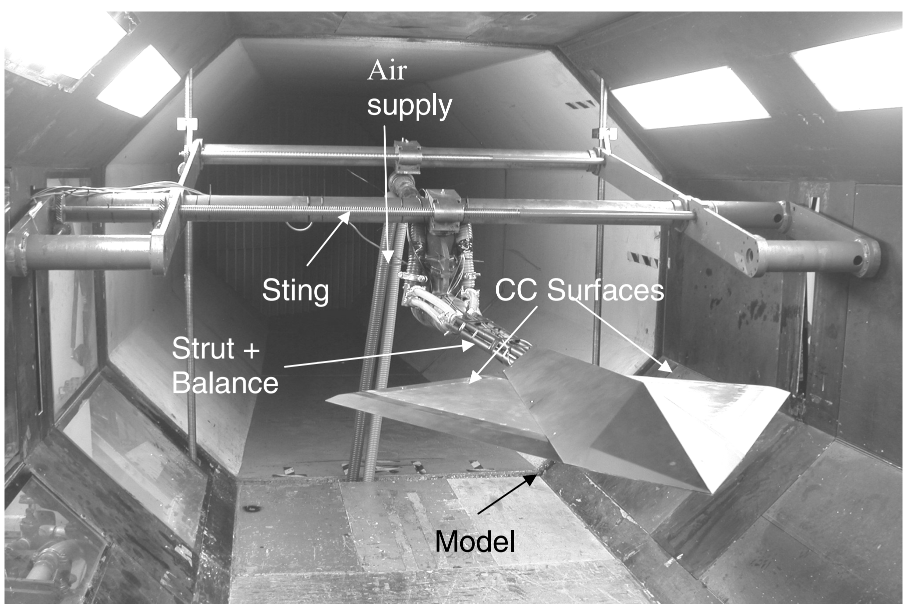

Figure 4: Sting-mounted model in wind tunnel

The air supply was again taken from pressurised tanks and passed through a series of flexible hose. Tare effects due to flexing of the hoses when under pressure were minimised by incorporating highly flexible hose within the model, adjacent to the calibration centre of the balance. Any tare effects due to any flexing of hoses were measured wind-off.

Preliminary tests were performed prior to data collection to determine efficiency of both Coanda surfaces, check for any leakages and uniformity of both slots. Test runs were made in the wind tunnel to examine model integrity and performance.

Tests were accomplished at 25m/s (a freestream Reynolds number of approximately 1.3×10^6) and the angle of attack was varied from 0° to 15° in 5° increments. The blowing was varied from zero to 0.004 at increments of 0.0005. Data was taken for various test parameters; symmetric blowing, in which the jet momentum from both plenums was identical, and asymmetric (or differential) blowing, in which only one side of the model would use the jet blowing.

5. Results 2

In quiescent conditions, both Coanda jets performed as expected, with the jets fully attaching to the Coanda surfaces. Figures 7 to 12 show the effectiveness of the full span model, in the form of carpet plots with contours of constant C_μ and angles of attack. A lift augmentation, $\left(\frac{\partial C_L}{\partial C_\mu}\right)$, of 10-25 was achieved, as demonstrated in figure 7, in which data is shown for both Coanda jets at the same mass flow rate, and therefore the same C_μ (symmetric blowing). Although the lift augmentation achieved is not as great as those achieved in other studies[7], it is believed that this can be attributed to the small radius of the Coanda surface. The trade-off of a lower lift augmentation is that the drag for such a surface is reduced when compared to traditionally large CC Coanda surfaces.

Assuming the centre of gravity to be at the quarter-chord position, the pitching moment about this point is nose-down (figure 8), which is as expected as the centre of lift is located aft of the quarter chord. It is encouraging to see that the circulation control device could be used to trim the aircraft, whilst maintaining high values of lift augmentation, as the variation in C_μ required at various angles of attack is approximately linear, as shown in figure 9. This suggests that the control of this parameter could be simply transferred to stick control in a real-flight situation.

The investigation in using circulation control for roll control revealed some interesting characteristics. The variation of lift with asymmetric blowing (zero blowing from the right Coanda jet) is shown in figure 10. Again, a lift augmentation of approximately 20-25 is achieved and it was demonstrated that the jet momentum is additive, that is, if the left jet was used at the maximum value of C_μ, the activation of the right jet would result in a similar lift curve to that obtained with symmetric blowing.

The control of rolling moment by circulation control is demonstrated in figures 11 and 12. It can be seen that a particular rolling moment can be achieved with a particular value of C_μ independent of the angle of attack, although the leading edge vortex, particularly effective at angles of attack from approximately 7.5°, produces an additional pro-roll moment. This pro-roll moment results from a secondary effect of the blowing tat enhances the vortex suction signature ahead of the blowing slot. This can be seen by the kink in the rolling moment curves. The data shows that, for example, a blowing coefficient of 0.0015 would be equivalent to an aileron deflection of approximately 5°. The slight negative rolling moment present at an angle of attack of 0° and $C_\mu = 0$ indicates that there is a slight model asymmetry, although this only equates to approximately 1 Nm of rolling moment.

6. Conclusions

An experimental investigation of circulation control, initially on a single delta wing configuration with varying trailing edge geometry and then on a full-span model, has been successfully completed.

The variation of slot height indicated that a smaller slot height yielded a higher lift augmentation, $\left(\frac{\partial C_L}{\partial C_\mu}\right)$. However, it is anticipated that there is a limiting height, requiring further work. Lift augmentations of approximately 10-25 for low blowing rates were obtained with both models. This suggests that useful lift increments can be obtained with C_μ's of the order 0.005, equivalent to those achieved using existing flap systems ($\Delta C_L \sim 0.1$). As the CC system is considerably less complex mechanically than other high lift devices, this may be significantly beneficial when contemplating maintenance, production costs and reliability.

Importantly, the production of roll moments can be superimposed on the lift generation, suggesting minimised interaction and simple control development.

More detailed work at even smaller increments of C_μ, especially in the lower blowing regions, will enable greater understanding of the physics involved in circulation control and the areas of higher lift augmentation. Further experimental work using the full-span model will continue to investigate the application of circulation control to roll control and pitch trim. The implementation of pulsed jets will also reduce the required mass flow bleed yet provide similar lift augmentations[3].

7. References

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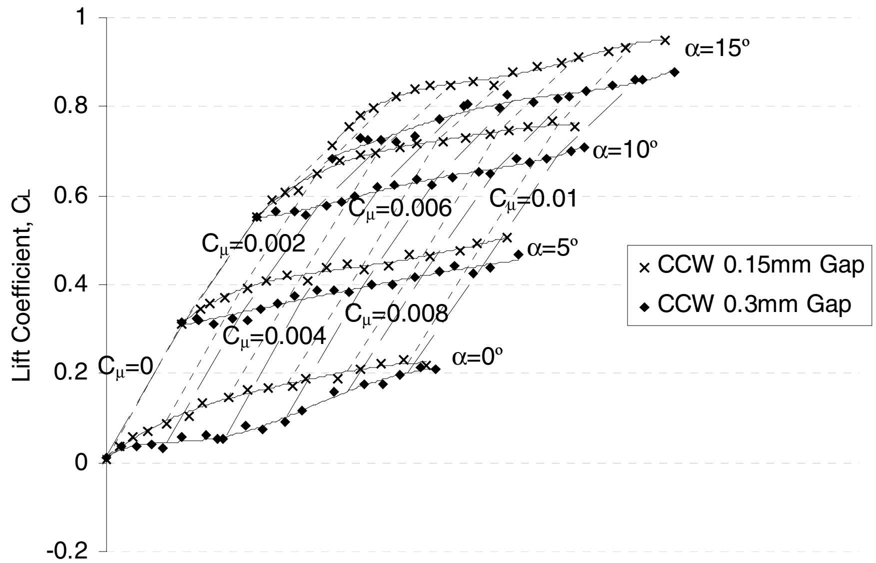

Figure 5: C_L v C_μ - Effect of slot height on circulation control

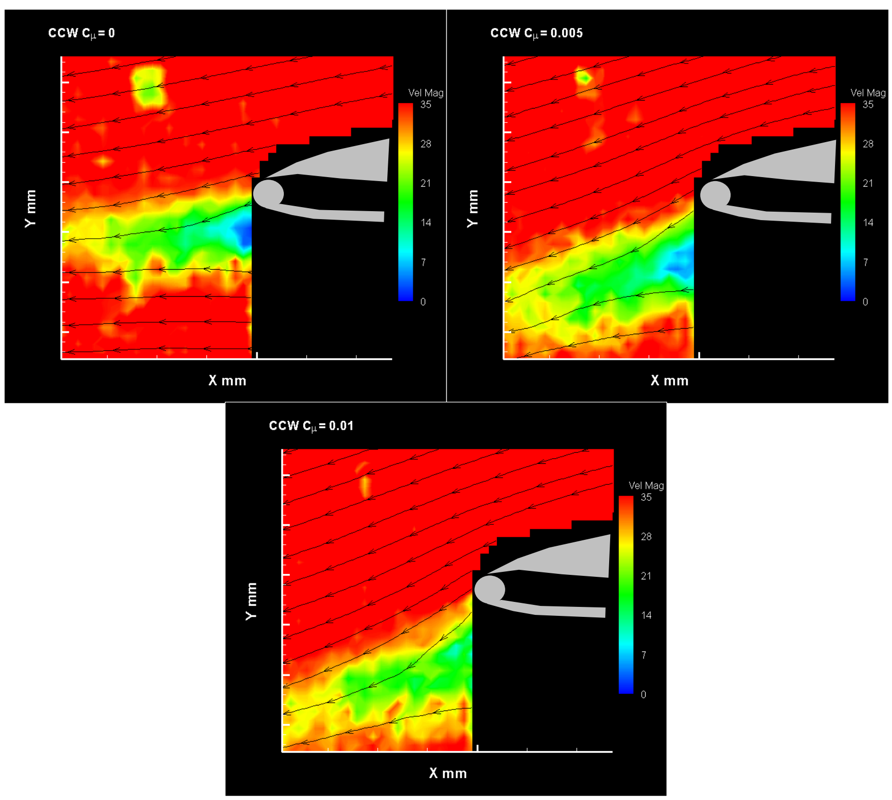

Figure 6: PIV velocity contour plots with streamlines obtained for angle of attack 10° at following blowing coefficients: a) C_μ = 0, b) C_μ = 0.005, c) C_μ = 0.01.

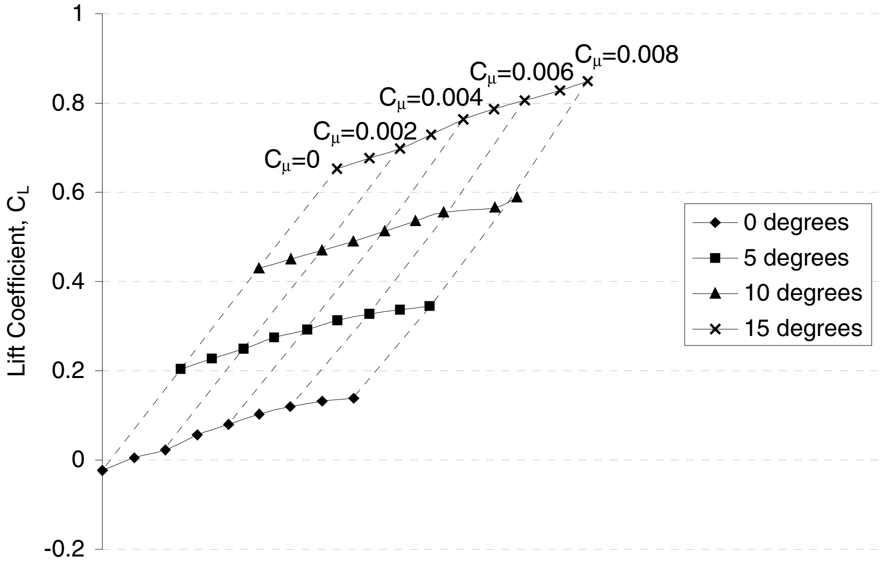

Figure 7: Variation of lift with both circulation control systems blowing with same mass flow rate (symmetric blowing).

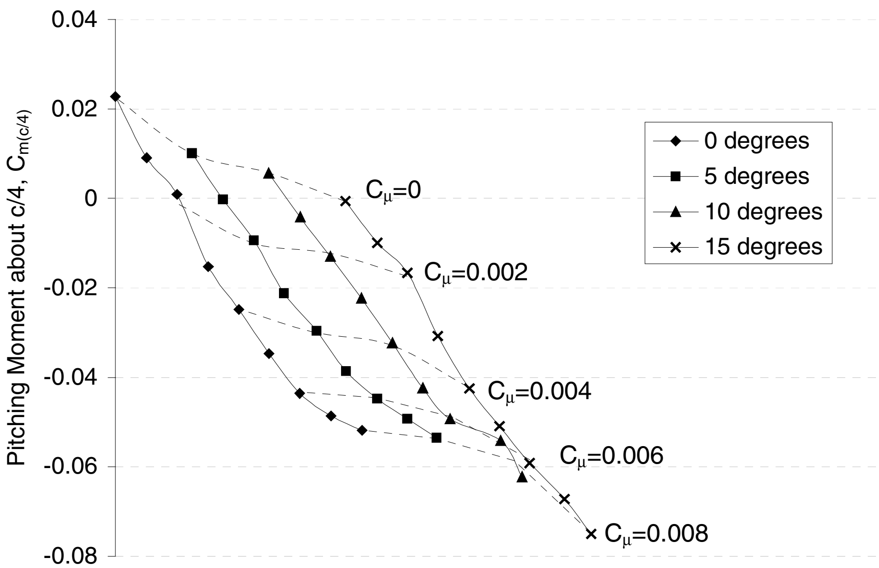

Figure 8: Variation of pitching moment about the quarter-chord position with both circulation control systems blowing with same mass flow rate (symmetric blowing).

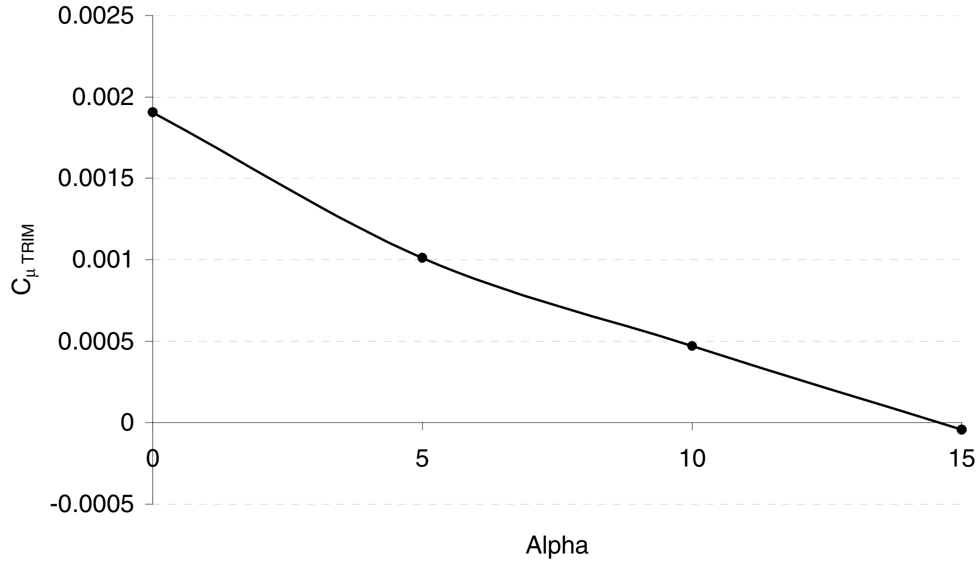

Figure 9: Blowing required for pitch trim at varying angles of attack with both circulation control systems blowing with same mass flow rate (symmetric blowing).

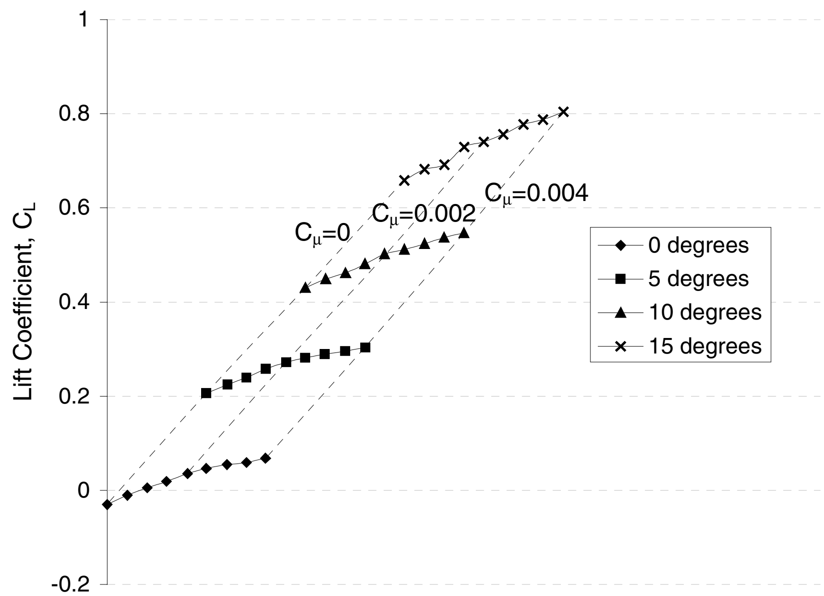

Figure 10: Variation of lift with only one circulation control system blowing (asymmetric blowing).

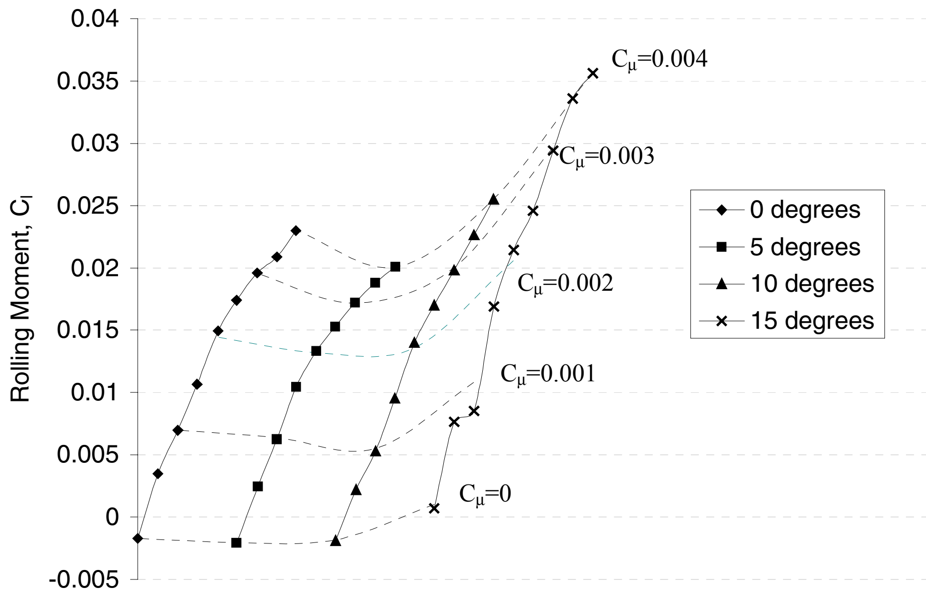

Figure 11: Variation of roll with only left circulation control system blowing (asymmetric blowing).

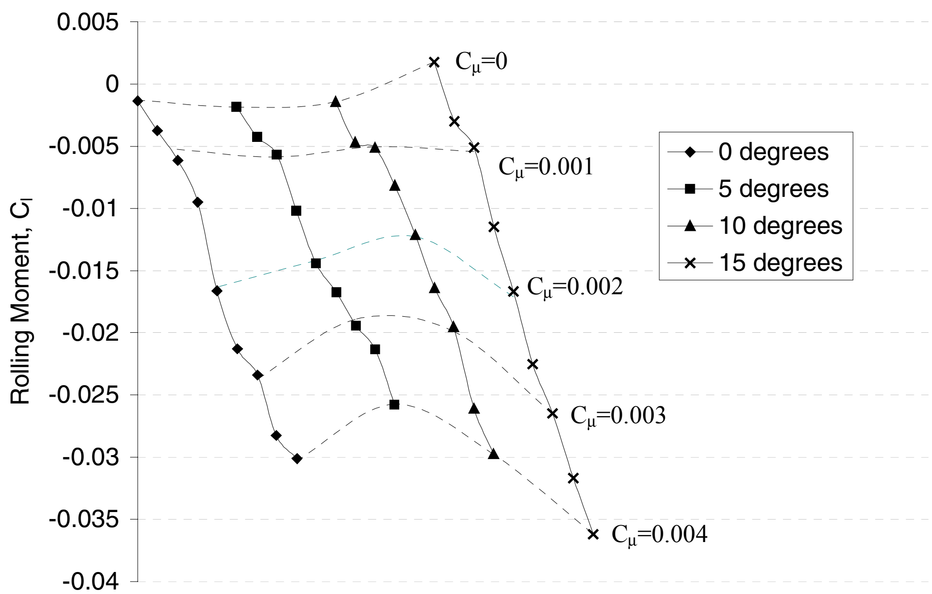

Figure 12: Variation of roll with only right circulation control system blowing (asymmetric blowing).