Development of a bi-directional circulation control actuator

A. Buonanno, M.V. Cook* and S.D. Erbslöh**
**Cranfield University*
School of Engineering, MK43 0AL, Cranfield UK

Abstract

Trailing edge blowing over a Coanda surface has been utilised as a circulation control mechanism for increasing the lift of an aircraft wing. Typically, high energy air is blown from a narrow span-wise slot over the rounded trailing edge of a wing and the air supply is modulated in some way to affect a degree of lift control on the wing. This mechanisation produces an aerodynamic force in a uni-directional sense only. An alternative novel flow control actuator is described which utilises a simple variable geometry Coanda surface with upper and lower span-wise blowing slots to achieve fully proportional bi-directional control in the manner of a conventional flap. A prototype device has been wind tunnel tested, is shown to have substantially linear response characteristics and to be as efficient as an equivalent flap surface.

Nomenclature

	Definition	*Units*
CC	Circulation Control	-
TE	Trailing Edge	-
b	wing span	m
c	wing chord	m
h_j	Jet slot height of conventional CC actuator	m
h_{ju}	Upper slot height of bi-directional CC actuator	m
h_{jl}	Lower slot height of bi-directional CC actuator	m
r	radius of trailing edge cylinder	m
α	angle of attack	degrees
δ	TE cylinder deflection	degrees

1. Introduction

In recent years there has been increasing interest in techniques to provide aerodynamic lift and control involving virtual aerodynamic shape change as opposed to a real mechanical shape change. Flapless control can potentially reduce the number of moving and electrical parts as well as weight. One technique which has been under investigation is circulation control of the lifting wing by means of trailing edge blowing using high pressure air bleed either from the thrust engine or additional air supply. The characteristic of a wall jet remaining attached to a curved surface is well known and dates back to 1800 when Young first described the phenomenon and which was later named the Coanda effect after Henri Coanda in 1910. The Circulation Control (CC) Wing concept is based on the application of the Coanda effect and involves converting the airfoil trailing edge into an enlarged rounded surface to which a jet of air adheres when blown tangentially from the upper surface. Circulation Control technologies have been around since the early 1930s and successfully demonstrated on a large number of applications. Utilizing this technology on a two dimensional airfoil of subsonic aircraft, lift augmentation of nearly 80 times the input blowing momentum has been reported.[1] Exploratory investigations have demonstrated a threefold gain in lift over the conventional flapped airfoil section and at least a doubling of maximum lift coefficient (C_L) for a three-dimensional aircraft configuration.[2,3] A detailed description of the CC concept and previous research work is given in reference.[4] However, so far research has considered the CC Wing concept mainly as a high lift device to improve cruise efficiency, take off field length and reduced landing approach speed. Application of the CC concept to a three dimensional aircraft wing was first demonstrated at West Virginia University in April 1974 on a CC Technology Demonstrator STOL aircraft, and in 1979 on a modified Navy Grumman A-6A aircraft.[5,6] More recently, academic research focused on the performance benefits of a CC delta wing with regions of separated flow was carried out at Manchester University.[7,8] A combined experimental and computational fluid dynamics study of the low speed aerodynamic benefit achievable through the application of CC to a delta wing was performed. This was perceived to offer the potential for replacement of conventional control surfaces with the blown trailing edge of a CC wing. The initial aim of the study was to assess the feasibility of the technology for application to a tailless concept during landing to reduce the pitch attitude and, or, landing speed whilst maintaining longitudinal trim. A generic model of a delta wing plan-form was tested and it has been shown that CC can produce a significant lift increment, similar to that of a conventional high lift control surface, but with a lower pitching moment increment, resulting in improved aircraft control. All configurations tested showed lift augmentation of approximately 15 for reasonably low blowing rates. This suggests that the usable lift increment, equivalent to that achievable with existing flap systems, could be obtained with blowing coefficient of order C_μ=0.005. Further experimental investigations have been performed by Frith and Wood focusing on potential manoeuvre performance with a CC wing.[9] An investigation into roll control was conducted at Manchester University on a full span test configuration with delta wing plan-form, using differential upper surface blowing on either side of the full span model.[10] The results indicated that roll control varies linearly with blowing momentum and the presence of the leading edge vortex augments the effect in a pro-roll capacity. A gradient of rolling moment curves with C_μ of approximately 7 was found and a blowing momentum coefficient of 0.0021, equivalent to an aileron deflection of 10 deg was obtained. This detailed aerodynamic work undertaken by Manchester University has established the operational principles for flapless control of air vehicles by flow control means utilising the Coanda effect. In particular, it has been demonstrated that a wing trailing edge incorporating a narrow span-wise slot through which high pressure air is blown over the Coanda surface can produce usable control forces and moments.

Modulation of the air supply to the slot by means of a control valve enables unidirectional force and moment generation for control of the vehicle. Replacing conventional ailerons with span-wise pairs of slots permits differential operation sufficient for lateral control and without the adverse yaw effect of an aileron flap surface. However, modulation of the resultant control force and moment generated by a fixed trailing edge geometry utilising internal air flow throttling implies relatively crude “bang-bang” control. Smooth proportional control by means of an air supply control valve suggests an unwieldy engineering solution to a practical mechanism for vehicle control. Potential engineering difficulties include increased mechanical complexity for bi-directional control, control bandwidth limitation associated with airflow throttling and, probably most significantly, the back pressure impact of on-off bleed air demand on a small gas turbine engine compressor.

2. A bi-directional actuator concept

An alternative CC mechanisation comprises an actuator device capable of proportional bi-directional control; the general arrangement of the flow control actuator concept is shown in Figure 1b with a conventional actuator depicted in Figure 1a. The small plenum chamber comprising the body of the device is envisaged as an interchangeable replacement for a conventional flap surface. The trailing edge of the actuator incorporates an upper and lower slot separated by a span-wise cylindrical bar which acts as the Coanda surface. The cylindrical bar is free to rotate eccentrically about its longitudinal (span-wise) axis, which is offset from its symmetrical axis, such that the upper and lower slots can be adjusted from fully open to fully closed in an asymmetric manner, with angular rotation of about ±15°. Thus by rotating the bar proportional bi-directional modulation of the forces and moments can be effected. The flow control actuator avoids some of the problems of the fixed slot arrangement described above. In particular, a continuous air supply is required, and since the total slot area remains constant, there is no back pressure effect on the source during normal operation. Also, since the device has only one moving part with minimal inertia a high operational bandwidth is possible. However, since the trailing edge slots and Coanda surface geometry are critical to the performance of the device, precision engineering accuracy is required if an appropriate level of control resolution is to be achieved. To validate the flow control actuator concept described above a feasibility study was undertaken using a symmetrical rectangular wing with a RAE 104 profile.

An interchangeable conventional control surface with 0.25b and 0.22c was implemented to act as the baseline reference. It was interchangeable with a CC actuator of equal span-wise extent, but reduced chord length due to the inset circular trailing edge. The wing area was decreased by about 2% with the CC actuator installed. The device consisted of two knife edges forming the upper and lower trailing edge surfaces of a simple plenum chamber fitted with a single air supply inlet on the port side. The moving cylindrical trailing edge Coanda surface was actuated by means of a small model servo driven from standard PC. The key geometric parameters for the test wing, flow control actuator and interchangeable flap are given in Table 1.

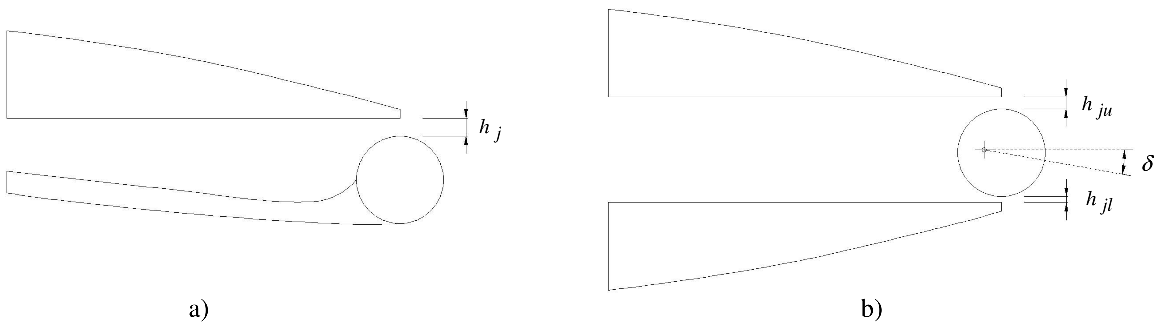
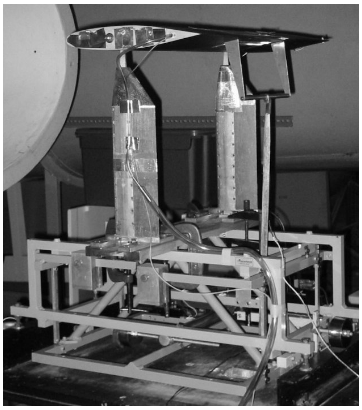


Figure 1: Section view of a wing trailing edge arrangement for a a) conventional and b) bi-directional circulation control actuator.

Table 1: Wing and actuator geometries			
		Test wing with flap	**Test wing with CC actuator**
Span (m)	b	0.6	0.6
Chord (m)	c	0.3	0.3
Thickness /chord ratio	t/c	0.15	0.15
Area (m^2)	S	0.180	0.177
TE thickness (mm)		1.0	5.0 (at actuator te)
Flap span (mm)		150	150
Flap chord (mm)		66	58
Coanda surface radius (mm)	r		2.5
Nominal slot height range (mm)	h		0.05 – 0.20

3. Experimental Setup

Wind tunnel tests were performed in an open jet subsonic wind tunnel at Cranfield University and a three component floor balance was used to measure the aerodynamic forces acting upon the wing. The experimental test rig comprising the wing mounted on the balance and placed in the working section is shown in Figure 2a. The blowing coefficient C_μ is the most critical parameter controlling the effectiveness of a CC actuator, an increase in C_μ resulting in an increase in lift. For fixed external conditions, i.e. a constant denominator, a large C_μ may be obtained by either a high mass flow and relatively low exit velocity or a high exit velocity with a relatively low mass flow. These traits may be explored by varying the jet exit area via the jet slot height, which herein is referenced to the Coanda surface radius, i.e. h/r. The trailing edge of the flow control actuator is shown in Figure 2b.



a) Rectangular wing installed on 3 component balance.

b) TE detail of bi-directional actuator.

Figure 2: Photographs of the experimental setup.

4. Results and discussion

It has been reported that smaller slot heights result in a larger return in lift at constant C_μ which implies that a high jet velocity/momentum are required for an effective actuator.[4] To confirm this tests were performed at constant free-stream Mach number while varying angle of attack (α), slot height (h/r) and blowing coefficient (C_μ). The results obtained are presented in Figure 3. The lift augmentation (dC_L/dC_μ) was in the range of 10-20, which was nearly constant for the largest two slot heights (h/r=0.06, 0.08) and within the range C_μ=0-0.02. A small h/r gave rise to a non-linear relationship with a notable change in the lift augmentation at ΔC_L=0.15-0.2. This may be attributed to the transition from boundary layer control to super-circulation.[4] Due to its highly linear behaviour the dual slot actuator was set up with the nominal upper and lower slot heights in the range $0.06 \leq h_0/r \leq 0.08$.

The dual slot actuator was operated with a constant plenum pressure corresponding to a total blowing coefficient of $C_{\mu,total}$=0.01, i.e. V_j/V_∞=5. In analogy with conventional control surfaces, the cylinder deflection δ is defined as positive if a negative response of the aircraft is the result. At the datum control angle δ=0° the upper and lower slots are of equal height and were set to give an equivalent total slot height of h/r=0.08. At the largest cylinder deflection (δ_{max}=13°) the lower slot was closed and the upper slot increased to h/r=0.08. The inherent limitation of the setup to position the knife edges sufficiently accurate caused misalignments which were relatively large and caused notable leakage through the closed slot. Therefore data presented herein will concentrate on cylinder deflection in the range of $-7° < \delta < 7°$.

The proof of concept for the dual slot actuator is given in Figure 4. For $C_{\mu,total}$=0.01 the lift coefficient is a linear function of actuator deflection with a maximum lift increment of $\Delta C_L=\pm 0.1$. The efficiency of actuation, in terms of $dC_L/d\delta$, increases with angle of attack with a maximum at α=8°, but further work is needed to confirm and clarify the significance of this phenomenon. A direct comparison to the performance of the flap has been made. For a cylinder deflection of δ=7° the equivalent flap deflection is around η=10°. The CC actuator therefore has an increased efficiency for C_μ=0.01:

$$\left[\frac{dC_L}{d\delta}\right]_{C_\mu=0.01} = 0.63 rad^{-1} \qquad \frac{dC_L}{d\eta} = 0.46 rad^{-1}$$

5. Conclusion

- A novel alternative to a conventional single slot trailing edge circulation control actuator has been developed that enables bi-directional control.
- The bi-directional actuator may act as a direct replacement of a conventional control surface and therefore enables flapless roll control.
- This actuator alleviates possible coupling with the air supply, in particular if engine bleed is used, as only a constant mass flow is required.
- Although this device is a first prototype a relatively high control efficiency could be achieved when compared to a conventional flap.
- Within the operational envelope reported, a remarkebly linear control response is apparent.

6. Further work

To enable further characterisation the actuator arrangement will be revised so that the test envelope can be expanded. In particular the mechanical accuracy of the device is in need of further improvement to alleviate any leakage at maximum cylinder deflection. Currently a CFD study is also underway to enable a more detailed description of the flow field.

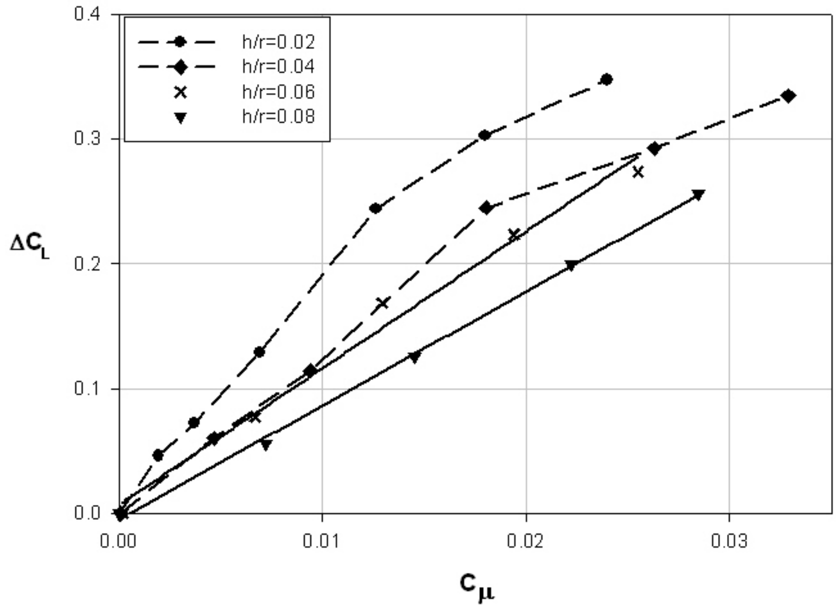


Figure 3: Effect of slot height on lift generation as a function of blowing momentum coefficient. Test conditions: $Re_\infty=1.4x10^5$, $\alpha=0°$, $C_{L0}=0$

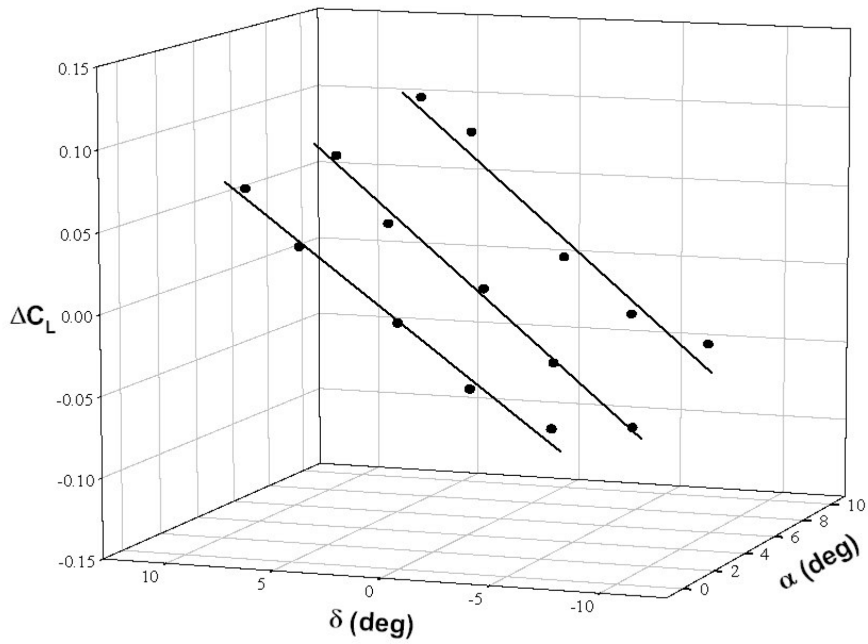


Figure 4: Lift coefficient with differential blowing vs. cylinder deflections for increasing angle of attack. Test conditions: $Re_\infty=1.4x10^5$, $C_{\mu,total}=0.01$, for $\delta=0°$ $h_{upper}=h_{lower}=0.1mm$.

7. References

[1] ENGLAR, R. J. & C. A. APPLEGATE, Circulation Control – A Bibliography of DTNSRDC Research and Selected Outside References (January 1969 to December 1983). DTNSRDC-84/052, September 1984.

[2] ENGLAR R.J., Subsonic Two-Dimensional Wind Tunnel Investigations of the High Lift Capability of Circulation Control Wing Sections. DTNRSDC Rept., ASED-274, April 1975.

[3] ENGLAR, R.J.,RODNEY, A. HEMMERLY, Design of the Circulation Control Wing STOL Demonstrator Aircraft. AIAA 79-1842R.

[4] ENGLAR, R.J., Circulation Control Pneumatic Aerodynamics: Blown Force and Moment Augmentation and Modification; Past, Present & Future. AIAA-2000-2541, Fluids 2000, Denver, Colorado, 2000.

[5] ROBERTS S. C., WVU circulation controlled STOL aircraft flight tests. West Virginia University, Morgantown, WV, Aerospace TR-42, July 1974.

[6] PUGLIESE A.J. Flight testing the circulation control wing. AIAA-79-1791, AIAA Aircraft Systems and Technology Meeting, 1978.

[7] SELLARS, N.D, WOOD N.J. & KENNAUGH A. Delta wing circulation control using the coanda effect. AIAA 1st Flow Control Conference, St. Louis, June 2002.

[8] WOOD N.J & ROBERTS L. The control of vortical lift on delta wings by tangential leading edge blowing. AIAA-87-0158, AIAA 25th Aerospace Sciences Meeting, Reno, Nevada, 1987.

[9] FRITH S. P &A WOOD N.J. Circulation control high lift applications on a delta wing. CEAS Aerospace Aerodynamics Research Conference, Cambridge, June 2002.

[10] FRITH S. P & WOOD N.J. Investigation of dual circulation control surfaces for flight control. AIAA 2004-2211, 2nd AIAA Flow Control Conference 28 June, Portland Oregon, July 2004.

This page has been purposedly left blank