A circulation control actuator for flapless flight control

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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 spanwise slot over the rounded trailing edge of a wing and the air supply is modulated to effect a degree of lift control on the wing. This configuration 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 spanwise blowing slots to achieve fully proportional bi-directional control in the manner of a conventional flap. A prototype device has been wind-tunnel tested and is shown to have substantially linear response characteristics and to be as efficient as an equivalent flap surface. The performance of a flow control actuator suitable for small UAV applications is described.

NOMENCLATURE

b	span
c	chord
$\bar{\bar{c}}$	mean aerodynamic chord
C_D	drag coefficient
C_L	lift coefficient
C_m	pitching moment coefficient
C_μ	blowing momentum coefficient
h	air jet slot height
K_μ	lift augmentation
m	mass
M	Mach number
Q	dynamic pressure
r	Coanda surface radius
R_e	Reynolds number
S	reference wing area
t/c	thickness to chord ratio
V	velocity
α	angle-of-attack
δ	control angle
Δ	increment
λ	Coanda surface axis offset
η	flap control angle
ρ	air density

Subscripts

0	nominal slot height
∞	free stream conditions
e	equivalent
j	jet slot
l	lower slot
u	upper slot

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Figure 1. The Eclipse air vehicle.

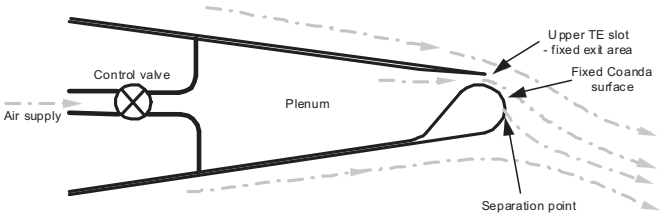


Figure 2. Fixed trailing-edge slot geometry.

1.0 INTRODUCTION

The five-year FLAVIIR research programme is supported jointly by the Engineering and Physical Sciences Research Council (EPSRC) and BAE Systems, and the objective is to design, build and fly an unmanned air vehicle (UAV) for the purpose of demonstrating a number of advanced technologies. Specialist research groups from ten universities are collaborating in the programme and project design integration is the responsibility of the School of Engineering at Cranfield University. The Demon air vehicle is the subject of the research programme and its configuration derives from Eclipse, a diamond wing tailless UAV designed at Cranfield and shown in Fig. 1. Eclipse has a wing span of 2·2m, an estimated flying weight of ~50kg, a maximum speed of about 120kt and is powered by an Olympus AMT gas turbine engine. It is anticipated that Demon will be a little larger than Eclipse.

A principal feature of the Demon aircraft variant is that the aerodynamic flap control surfaces shall be replaced with flow control mechanisms sufficient to demonstrate total flapless flight control of the vehicle. In the context of the experimental programme, the vehicle will be fitted with both flapless and conventional flap controls such that it will be controllable by either means, or by a combination of both.

Two flow control mechanisms for flapless flight control are being developed for Demon. The first utilises engine thrust vectoring for pitch control by means of secondary blowing over fixed upper and lower Coanda surfaces installed in the rectangular exhaust nozzle. The second utilises wing circulation control (CC) in place of conventional ailerons for roll control. The CC 'aileron' control also utilises blowing over a Coanda surface embedded in the trailing edge of the wing. Both flow control mechanisms require a continuous and substantial supply of air and this will be bled from the engine compressor or produced by an auxiliary power unit.

In support of the FLAVIIR programme, the Aerodynamics Department at Manchester University has made a substantial contribution to the development of flow control technology both for thrust vectoring and for circulation control. Wide ranging research into flow physics and the application of flow control to aircraft flight control has been made over a period of many years, see for example, Wood *et al*[1-4]. Recently completed flow control research with direct relevance to the FLAVIIR programme was completed by Frith[6] and this reference includes a substantial and useful aerodynamic data base. A review of this material raised the obvious question; 'How to control the flow in a manner compatible with conventional aircraft flight control?' Consideration of this question led eventually to the bi-directional flow control actuator solution described in the following paragraphs.

The dual slot concept for circulation control is not new and has been addressed by the GACC test program[7]. A 2D general aviation circulation control airfoil model with dual slot that utilises a pulsed pneumatic flap was designed and tested. The main objective of the research was to reduce mass flow rate requirements for a given lift performance, and reduce cruise drag penalty for STOL applications. Another example of modulated/vectored blowing is presented in Ref. 8, in which the concept consisted of an elliptical wing section with blowing modulation using piezoelectric actuation. The concept shows the advantage of modulating the blown air in response to command signals. An alternative variation is presented in this paper in which steady jet slot blowing over a Coanda surface is used. Proportional bi-directional modulation of the aerodynamic force and moment is achieved by steady blowing through upper and lower variable geometry trailing-edge slots. Slot geometry is modulated by eccentric rotation of a span-wise cylindrical bar that separates the slots and acts as the Coanda surface.

Thus, this paper describes a novel alternative engineering solution to the circulation control problem. A flow control actuator concept has been developed as a simple direct replacement for a conventional aerodynamic flap surface, and which could be used as an aileron, elevator or rudder.

2.0 PRINCIPLE OF OPERATION

The aerodynamic research undertaken by Manchester University has established the operational principles for practical 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 spanwise slot through which high pressure air is blown over the Coanda surface can produce usable control forces and moments. The arrangement successfully demonstrated in wind-tunnel tests and on a flying model aircraft at Manchester is shown in Fig. 2.

Modulation of the air supply to the slot by means of a control valve enables uni-directional force and moment generation for control of the vehicle. Replacing conventional ailerons with spanwise 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 fixed trailing edge geometry, utilising internal air flow throttling, raises the engineering challenge of avoiding the worst effects of dynamic interaction between the air supply system components. Thus smooth proportional control by means of an air supply control valve suggests a less amenable engineering solution to a practical mechanism for vehicle control. Potential engineering difficulties include increased mechanical complexity for bi-directional control, control lag associated with airflow throttling and, probably most significantly, the back pressure impact of intermittent bleed air demand on a small gas turbine engine compressor.

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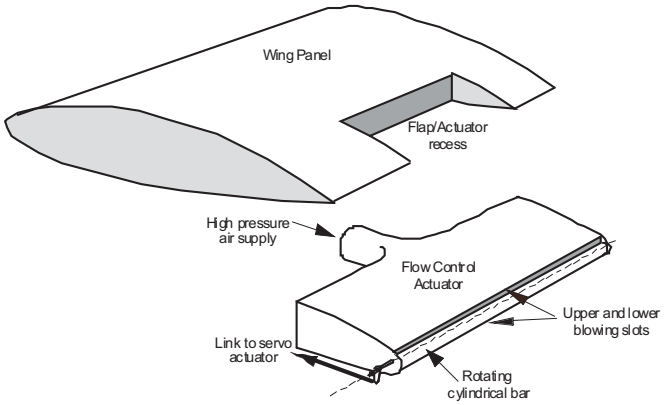


Figure 3. General arrangement of a flow control actuator installation.

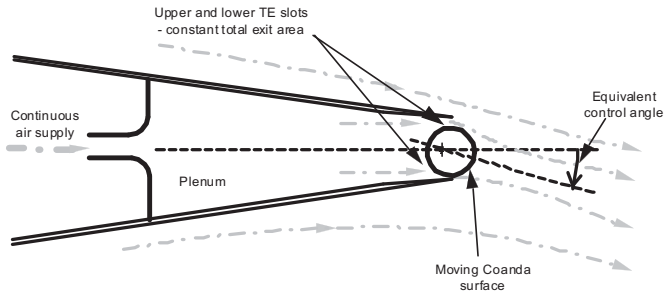


Figure 4. Cross section of the flow control actuator.

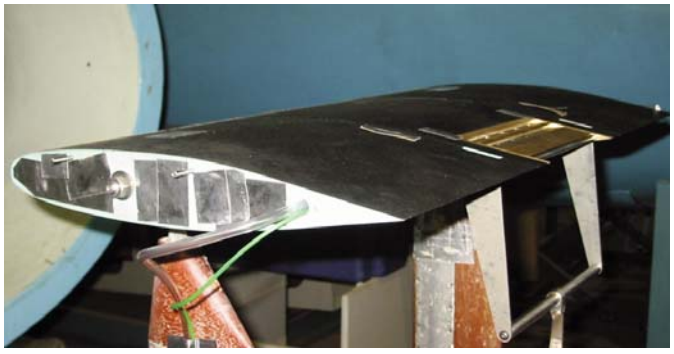


Figure 5. Test wing with installed actuator.



Figure 6. Trailing-edge view of the flow control actuator.

3.0 A CIRCULATION CONTROL ACTUATOR CONCEPT

An alternative CC mechanisation developed at Cranfield comprises an actuator device capable of proportional bi-directional control; the general arrangement of the flow control actuator concept is shown in Fig. 3. The small wedge shaped plenum chamber comprising the body of the device is envisaged as an interchangeable replacement for a conventional flap surface as shown.

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. A cross section of the trailing edge of the device is shown in Fig. 4. 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 lift force can be effected.

The flow control actuator avoids some of the problems of the fixed slot arrangement described above. In particular, a continuous uninterrupted air supply is required, and since the total slot area remains constant, there is no back pressure effect on the air supply source during normal operation. Since the device has only one moving part with minimal inertia a high operational bandwidth is possible, and since there is no air flow throttling control lag is insignificant. 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.

In order to test the concept a prototype flow control actuator was designed and manufactured at a scale compatible with the Demon air vehicle. To facilitate wind tunnel testing the device was inserted into the trailing edge of a rectangular wing panel in place of a conventional interchangeable flap surface. The general arrangement may be seen in Fig. 5 and Fig. 6.

The test wing panel was manufactured with a symmetric RAE 104 aerofoil section, which is the same as that used for the outboard section of the Demon wing. The key geometric parameters for the test wing, flow control actuator and interchangeable flap are given in Table 1.

The interchangeable conventional flap control was implemented to provide a nominal aerodynamic performance reference for comparison. The CC actuator is of equal span-wise length to the flap but has reduced chord due to the inset cylindrical trailing edge. This results in a reduction in the gross wing area of about 2% with the CC actuator installed. The flow control actuator consists of a simple wedge shaped plenum chamber, the upper and lower trailing-edge surfaces of which have adjustable knife edges to set the slot heights above and below the cylindrical Coanda surface. High pressure air is supplied to the plenum chamber by means of an internal pipe connection, and the Coanda surface is actuated by means of a small model control servo driven from a standard PC.

Table 1
Test 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

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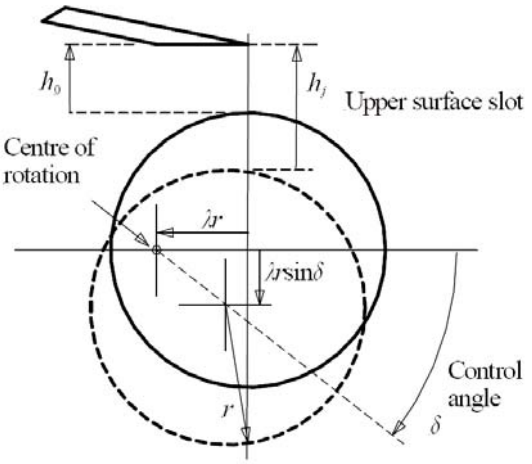


Figure 7. Flow control actuator slot geometry.

4.0 MATHEMATICAL MODEL

The upper surface exit slot geometry of the flow control actuator is shown in Fig. 7, the lower slot being geometrically similar is not shown. The control angle δ defines the Coanda surface movement about the centre of rotation and is positive as indicated — a positive control angle results in a positive lift increment. The upper and lower slot height is h_o when the control angle is zero. The offset of the centre of rotation from the axis of the Coanda cylindrical surface is denoted λr, where r is surface radius. Thus, referring to the geometry in Fig. 7, it is easily shown that the upper and lower slot height varies as a function of control angle as follows. For the upper slot,

$$h_{j_u} = h_0 + r + r\left(\lambda \mathrm{Sin}\delta - \sqrt{1-\lambda^2\left(1-\mathrm{Cos}\delta\right)^2}\right) \quad \ldots (1)$$

And for the lower slot,

$$h_{j_l} = h_0 + r - r\left(\lambda \mathrm{Sin}\delta + \sqrt{1-\lambda^2\left(1-\mathrm{Cos}\delta\right)^2}\right) \quad \ldots (2)$$

Now the lift developed by blowing high pressure air through a slot is governed by the blowing momentum coefficient C_μ, which for a part span slot is given by,

$$C_\mu = \frac{\dot{m}_j V_j}{QS} = \frac{\rho h_j b_j V_j^2}{\frac{1}{2}\rho V_\infty^2 S} = \frac{2h_j b_j}{\bar{\bar{c}}b}\left(\frac{V_j}{V_\infty}\right)^2 \quad \ldots (3)$$

Thus the upper and lower slot blowing momentum coefficient variation with control angle is given by substituting Equations (1) and (2) into Equation (3),

$$C_{\mu_u} = \frac{2rb_j}{\bar{\bar{c}}b}\left(\frac{V_j}{V_\infty}\right)^2\left(\frac{h_0}{r}+1+\left(\lambda \mathrm{Sin}\delta - \sqrt{1-\lambda^2\left(1-\mathrm{Cos}\delta\right)^2}\right)\right)$$

$$C_{\mu_l} = \frac{2rb_j}{\bar{\bar{c}}b}\left(\frac{V_j}{V_\infty}\right)^2\left(\frac{h_0}{r}+1-\left(\lambda \mathrm{Sin}\delta + \sqrt{1-\lambda^2\left(1-\mathrm{Cos}\delta\right)^2}\right)\right) \quad \ldots (4)$$

It follows directly that the upper and lower slot incremental blowing momentum coefficients due to control angle are given by,

$$\Delta C_{\mu_u} = \frac{2rb_j}{\bar{\bar{c}}b}\left(\frac{V_j}{V_\infty}\right)^2\left(\lambda \mathrm{Sin}\delta - \sqrt{1-\lambda^2\left(1-\mathrm{Cos}\delta\right)^2}\right)$$

$$\Delta C_{\mu_l} = -\frac{2rb_j}{\bar{\bar{c}}b}\left(\frac{V_j}{V_\infty}\right)^2\left(\lambda \mathrm{Sin}\delta + \sqrt{1-\lambda^2\left(1-\mathrm{Cos}\delta\right)^2}\right) \quad \ldots (5)$$

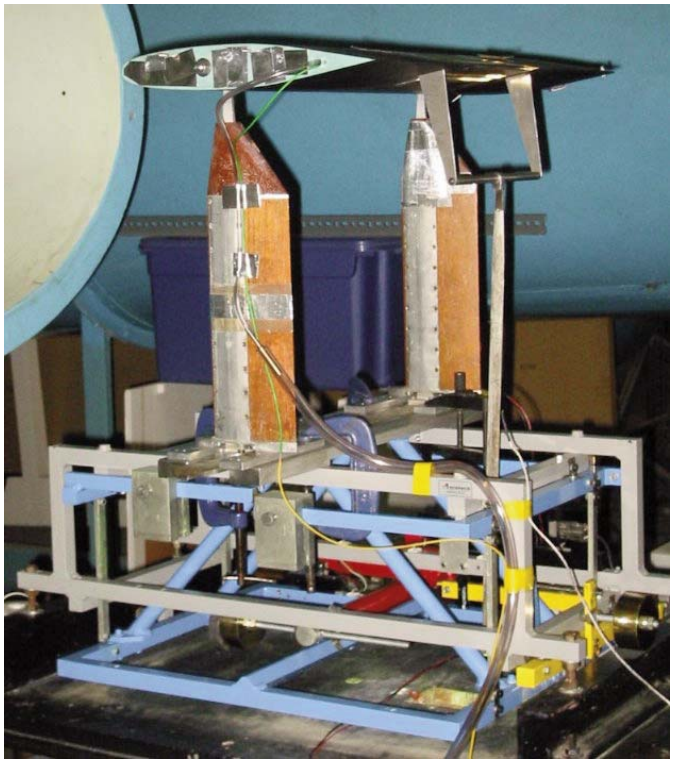


Figure 8. Wind-tunnel test installation.

Lift augmentation due to blowing is defined,

$$K_\mu = \frac{\partial C_L}{\partial C_\mu} \quad \ldots (6)$$

and based on empirical information K_μ is observed to be approximately constant for a given configuration. Now the lift increment due to upper slot blowing is positive and the lift increment due to lower slot blowing is negative, thus the total lift increment due to the combined effect of both slots is given by,

$$\Delta C_L = K_\mu\left(\Delta C_{\mu_u} - \Delta C_{\mu_l}\right) \quad \ldots (7)$$

The lift increment due to control angle follows directly by substituting Equations (5) into Equation (7),

$$\Delta C_L = K_\mu \frac{2rb_j}{\bar{\bar{c}}b}\left(\frac{V_j}{V_\infty}\right)^2 \lambda \mathrm{Sin}\delta \cong 2K_\mu\left(\frac{\lambda r b_j}{S}\right)\left(\frac{V_j}{V_\infty}\right)^2 \delta \quad \ldots (8)$$

since typically the control angle is small and $\delta < \pm 20°$.

5.0 WIND-TUNNEL TESTS

The test wing was mounted on a three component balance and installed in a low-speed open-jet wind-tunnel as shown in Fig. 8. Connections to the wing comprised the electrical servo drive and high pressure air from the laboratory supply via a regulator valve. Typically, the regulator valve was preset to provide the required blowing conditions for a given slot geometry. Experimental variables were tunnel velocity, wing angle-of-attack, control angle, actuator slot geometry and plenum air pressure. Measured aerodynamic parameters were lift, drag and pitching moment.

Initial tests were made to characterise the aerodynamic properties of the wing and to quantify the performance of a conventional inset flap in place of the flow control actuator for the purposes of comparison.

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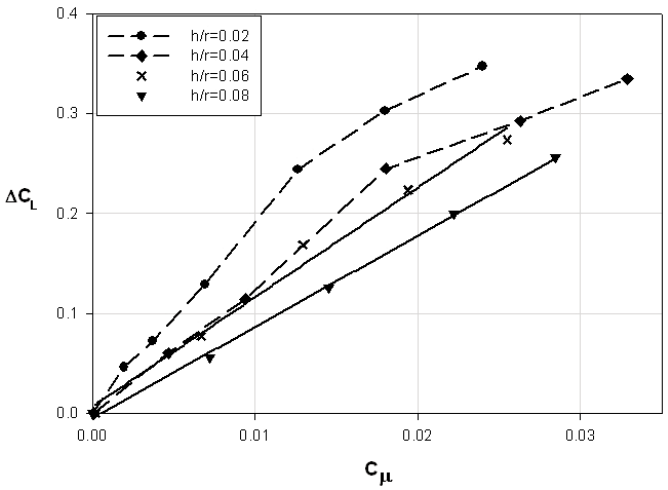


Figure 9. Effect of slot height on lift generation as a function of blowing momentum coefficient. Test conditions: $Re_\infty = 14 \times 10^6$, $\alpha = 0°$.

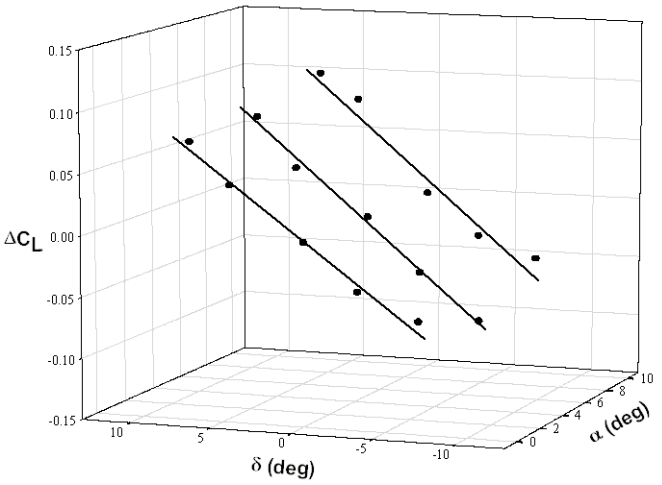


Figure 10. Incremental lift coefficient as a function of control angle and angle-of-attack. Test conditions: $Re_\infty = 136135$, $C_\mu = 0{\cdot}01$, nominal $h_0 = 0{\cdot}1$mm.

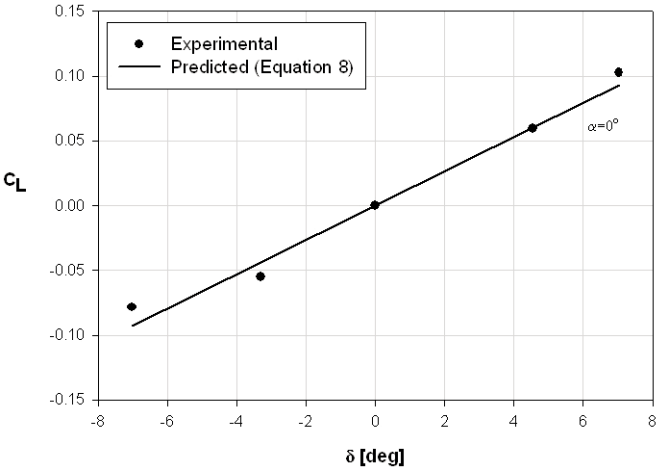


Figure 11. Comparison of the mathematical model with the experimental data.

Preliminary tests of the flow control actuator were made to establish a suitable working range for actuator slot geometry. This was done by fixing the Coanda surface to close the lower slot completely. The upper jet slot height was then varied by adjusting the upper rear knife edge of the plenum chamber and measurements were made with several alternative fixed upper slot geometries. Having established a suitable range of values for the jet slot height and the blowing momentum coefficient a limited series of experimental tests were made sufficient to prove the viability of the concept.

6.0 JET SLOT SIZING EXPERIMENT

The results of the initial jet slot height h/r optimisation experiments are shown in Fig. 9 for a typical range of values of blowing momentum coefficient. The tests were performed at a constant free-stream tunnel velocity of $V_\infty = 25 ms^{-1}$ for varying angle-of-attack α, jet slot height h/r and blowing coefficient C_μ. It is evident that a smaller slot height results in a greater lift increment for a given value of C_μ which implies that a high jet velocity/momentum is required for an effective actuator[1]. The achieved lift augmentation was in the range $10 \le K_\mu \le 20$ and was nearly constant for the largest two slot heights evaluated, $h/r = 0{\cdot}06$ and $h/r = 0{\cdot}08$ over the range of blowing momentum coefficient $0 \le C_\mu \le 0{\cdot}02$. Smaller values of h/r gave rise to a non-linear relationship with a notable change in the lift augmentation for $\Delta C_L \ge 0{\cdot}2$ as evident in Fig. 9.

In order to achieve good control linearity the dual slot actuator was set up with the nominal upper and lower slot heights in the range $0{\cdot}06 = h_0/r \le 0{\cdot}08$. This implies a lift augmentation of the order of $K_\mu \cong 9$. The 'control power' could be set by adjusting the blowing momentum coefficient C_μ.

7.0 FLOW CONTROL ACTUATOR PERFORMANCE

For the main series of tests undertaken the dual slot flow control actuator was set up to operate at constant plenum pressure corresponding to a total blowing coefficient of $C_\mu = 0{\cdot}01$, i.e. $V_j/V_\infty = 5$ where, for present purposes, V_∞ is representative of the Demon flight envelope velocity. At the datum control angle $\delta = 0°$ the upper and lower slots are of equal height and were set to give an equivalent total slot height of $h_0/r = 0{\cdot}08$. The Coanda cylinder rotation was physically limited by the engineering design of the actuator and at the largest angular deflection $\delta_{max} = \pm 13°$, the lower slot was closed and the upper slot was fully open with actual slot height $h_0/r = 0{\cdot}08$. An inherent limitation of the mechanical design of the actuator made it difficult to position the slot knife edges due to small misalignments, which were large enough to cause significant leakage through the closed slot. Therefore, it was found that useable data could only be obtained for Coanda cylinder rotation in the range $\delta = \pm 7°$. The proof of concept for the dual slot actuator is shown in Fig. 10. For $C_\mu = 0{\cdot}01$ the variation in incremental lift coefficient with control angle is close to a linear function with a maximum lift increment in the order of $\Delta C_L = \pm 0{\cdot}1$.

Experimental data from Fig. 10 corresponding with $\alpha = 0°$ have been fitted with the function given by Equation (8), where $K\mu$ is taken as the lift augmentation of an equivalent single slot actuator operating at the same conditions. The result is shown in Fig. 11 and it is evident that the device is capable of substantially linear performance. This observation is repeated over the working range of angle-of-attack of the wing.

To evaluate the control effectiveness of the flow control actuator its performance was compared with that of an equivalent span flap. Clearly, the comparison is of limited value since the flap performance

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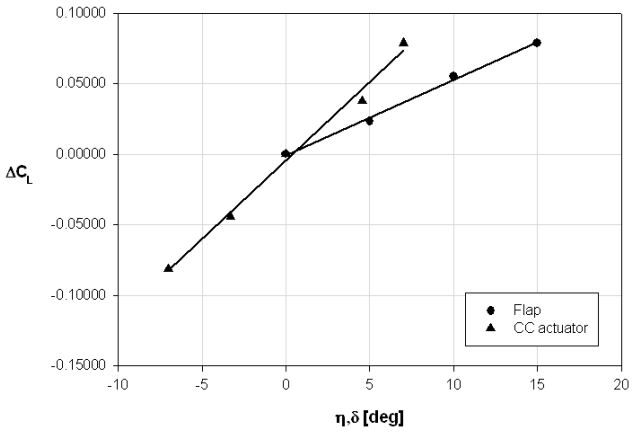


Figure 12. Comparison of flap and actuator control effectiveness. Test conditions: Re_∞ = 1·4 x 10^6, C_μ = 0·01, α = 5°.

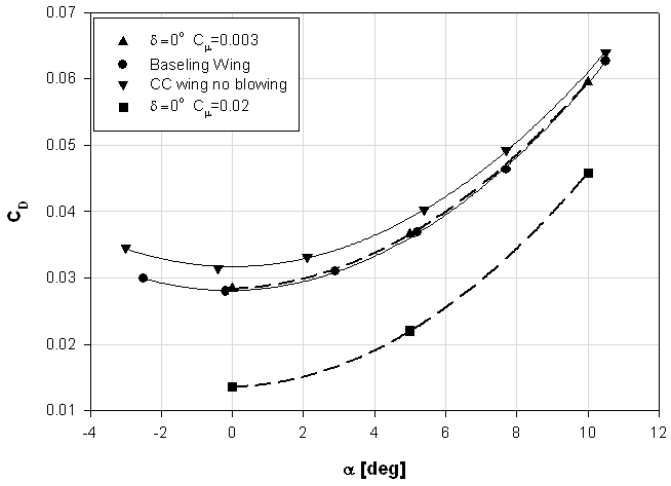


Figure 13. Comparison of the clean wing drag with flap and with actuator: Test conditions: Re_∞ = 1·4 x 10^6.

is a function of its chord and span, whereas the actuator performance is a function of span and blowing coefficient C_μ. However, since the input command to both controls is an angular displacement derived from a standard servo-actuator, it is interesting to compare the effectiveness of two similar sized installations. The comparison is shown in Fig. 12 where the incremental lift is plotted as a function of flap deflection angle η and actuator control angle δ. In spite of the limited scope of the experiment it is clear that both characteristics are essentially linear and have similar levels of performance. The control angle range for the flap over which data were obtained is ±30°, which exceeds what would normally be required for actual vehicle control. On the other hand, the flow control actuator angular input range was limited to ±7° for the practical reasons explained previously. The measured lift curve slope of both controls is,

$$\left[\frac{dC_L}{d\delta}\right]_{C_\mu=0\cdot01} = 0\cdot59\text{rad}^{-1} \quad \frac{dC_L}{d\eta} = 0\cdot3\text{rad}^{-1}$$

and clearly the flow control actuator is the more effective of the two controls for the given actuator configuration and limited range of operation compared.

Optimising the actuator geometry or increasing the blowing momentum coefficient would improve the actuator effectiveness

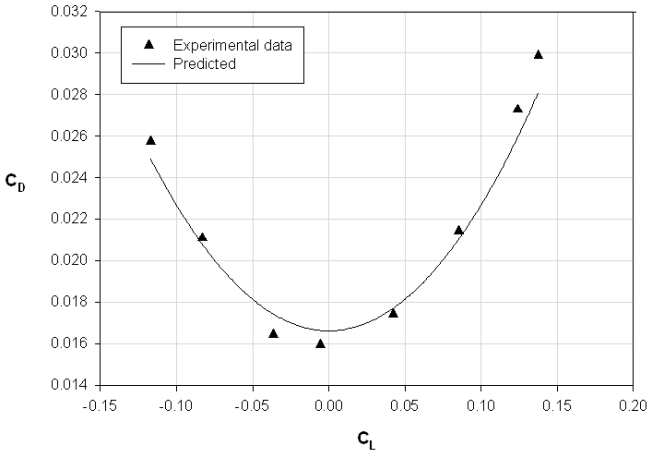


Figure 14. Comparison of the test wing drag polars with CC actuator. Test conditions: Re_∞ = 1·4 x 10^6, C_μ = 0·015, α = 0°.

further, but this demands higher air supply pressure and mass flow rate. Improved engineering design would enable an actuator control angle range, of say δ = ±15° or more, with comparable exit slot geometry and clearly, this would result in a significantly more effective control motivator.

Estimating the drag properties of the installed flow control actuator is an altogether more difficult task. The drag of the test wing with the flap and with the flow control actuator in place was measured for the typical angle-of-attack range. In both cases the control was set at the datum (un-deflected) angle, and in the case of the flow control actuator the total equivalent blowing momentum coefficient was varied. The 'clean' wing drag comparison is shown in Fig. 13. The drag coefficient with the flow control actuator installed takes into account the blowing momentum of the slot efflux.

With slot air supplies off, the measured drag coefficient of the CC wing at zero lift was found to be C_{Do} = 0·0317, which is about 15% larger than that of the conventional wing with the usual sharp trailing edge. However, the drag penalty associated with the blunt trailing edge of typical CC configurations is easily overcome by having the dual slot arrangement with steady blowing. In fact, by suitable adjustment of the blowing conditions at the exit slots, it is possible to cancel the base drag of the actuator by the small thrust generated at the slot exits. Thus, overall the drag is reduced as expected due to the decreased flow separation on the wing and due to the effect of the forward thrust of the jet at the slot exits.

Figure 14 shows the drag polar for an increasing deflection of the actuator control angle. Experimental data have been fitted with the function given by Equation (9), where K_1 is the induced drag coefficient of the wing and K_2 is taken as induced drag coefficient of the flap operating at the same conditions. It can be shown that the induced drag for lift developed by circulation control is essentially the same as that from conventional flap.

$$C_D = C_{D_0} + K_1 C_L(\alpha, C_\mu = 0)^2 + K_2(\Delta C_L(C_\mu,\delta))^2 - C_\mu \text{Cos}(\delta) \qquad \ldots (9)$$

When circulation control is employed, the value of C_D requires an additional 'correction' term to develop an expression for lift to drag ratio comparable with that of a conventional airfoil. According to Wood and Nielsen[1] some account should be taken of the power required to produce the kinetic energy of the jet, and it is suggested that the incremental drag coefficient associated with the kinetic energy of the jet may be described,

$$\Delta C_D = \frac{1}{V_\infty}\frac{d(KE)}{dt} = C_\mu \frac{V_j}{2V_\infty} \qquad \ldots (10)$$

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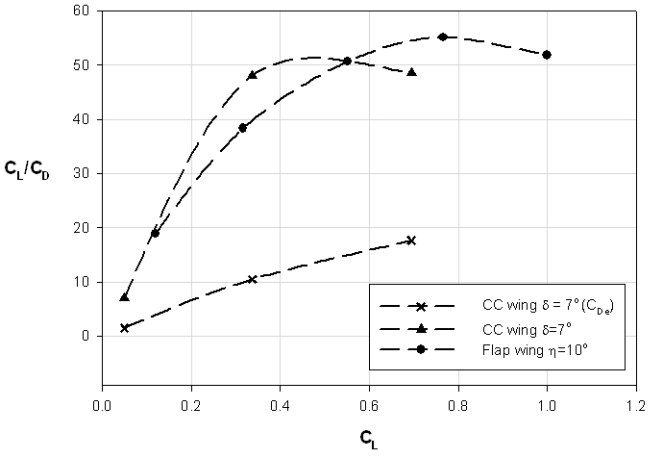


Figure 15. Comparison of the test wing efficiency with flap and with actuator: Test conditions: Re_∞ = 1·4 x 10^6, C_μ = 0·01, 0 < α <14°.

With this correction the equivalent drag coefficient of the wing with flow control actuator becomes,

$$C_{D_e} = C_D + C_\mu \frac{V_j}{2V_\infty} \quad \ldots (11)$$

The ratio of lift to equivalent drag based on Equation (11) is given in Fig. 15. It is evident that the overall efficiency of the wing with flap is higher, although it should be noted that the energy required to actuate the flap is not taken into account. However, the lower lift to drag ratio of the wing with flow control actuator is due to the second term in Equation (11) and is related to the compressor power required to generate the air supply energy.

7.0 CONCLUSIONS

Preliminary experimental evaluation has shown the flow control actuator concept to be a practical solution to the problem of direct flow control at subsonic velocities. At a relatively modest blowing momentum coefficient ($C_\mu \approx 0{\cdot}01$) the aerodynamic performance of the device is as good as an equivalent sized conventional flap control and the response characteristic is essentially linear. The experiments have also shown that the bi-directional nature of control remains fully functional up to the limit of the bandwidth of the model aircraft servo (approximately 20rad/s) used to actuate the Coanda surface. Thus, since the bandwidth of the servo is much greater than that of the UAV, the dynamic performance of the flow control actuator is entirely compatible with the control requirements of subsonic UAVs.

The performance of the prototype actuator was limited by some features of its engineering design. However, with improved design it should be possible to develop the capability of the actuator to improve its range, resolution, weight and compressed air consumption to provide a compact, robust and modular alternative to a conventional flap for use in small scale air vehicles. The potential of the device has been recognised by BAE Systems who have recently filed a patent application[5].

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