A REVIEW OF CURRENT LEADING EDGE DEVICE TECHNOLOGY AND OF OPTIONS FOR INNOVATION BASED ON FLOW CONTROL.

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Abstract.

An innovative step change is required to improve or replace the current mechanically deployed leading edge high lift systems for civil transport aircraft. This paper provides a review of existing leading edge device technologies for high lift and possible future technologies based on flow control. There is an emphasis on those flow control technologies that will be sufficiently mature enough for implementation within the next decade. The characteristics of the flow control technologies are presented with regard to the practical implications of the implementation of a design.

Nomenclature.

C_L	Lift coefficient	U_C	Cylinder surface velocity
C_{Lmax}	Maximum lift coefficient	α_{stall}	Stall angle of incidence
C_D	Drag coefficient	α_{max}	Max angle of incidence
h	Height (inches)	ΔC_L	Change in C_L
Hz	Hertz	δ	Boundary layer depth
U	Free stream velocity		

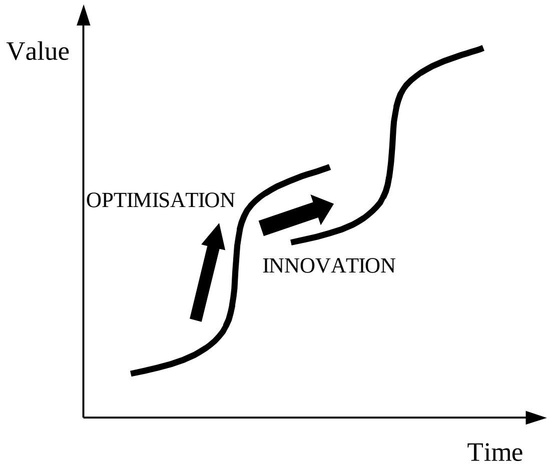
Abbreviations

Db(A)	Decibels
L/D	Lift to drag ratio
LE	Leading edge
LFC	Laminar Flow Control
nm	Nautical miles
VC	Variable camber

Introduction.

Aircraft manufacturers are under economical and environmental pressures to produce short and/ or long haul aircraft that are even more efficient are of simpler design and have reduced manufacturing and maintenance costs. Increases in overall product efficiency translate directly into improvements in fuel burn and cheaper, simpler and lighter aircraft will lead to lower operating, maintenance and purchase costs. Simultaneously, there is a need to achieve larger increases in lift co-efficient for a given angle of attack and increases in maximum lift, producing even greater payload over a specified range [3]. Improvements in high lift performance will allow the operator to take off and land with less noise for a given level of fuel burn and improved aerodynamic performance can be “traded” in many ways during the total integrated wing/ high lift system design. The total elimination of traditional high lift systems, for instance, would allow for an increase in the fuel tank volume and give the aircraft a greater range and reduced weight.

Traditional high lift systems are now highly evolved with only a small improvement in aerodynamic performance possible [4]. The practical implications of this are that current state of the art high lift systems are now very sensitive to deployment location. Meeting the demands of that sensitivity in real terms requires expensive, complicated and heavy mechanical systems. The value added to a system over time, its evaluation, and the choice between further optimisation and innovation is represented in Figure 1, “Technical evolution “S” curves”.



Technical evolution “S” curves

Figure 1

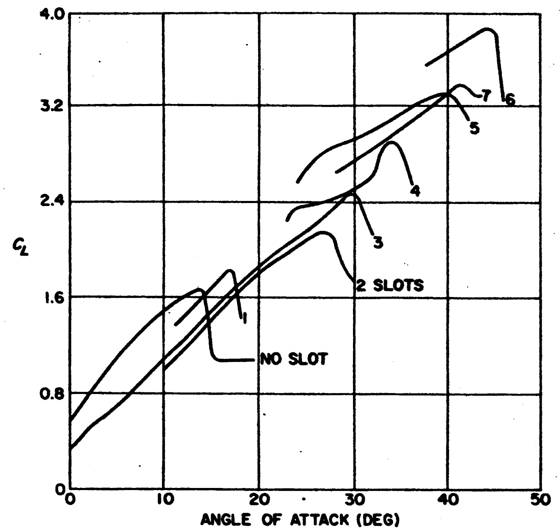
Figure 1 also shows that when evolutionary changes have refined the product to its maximum then an innovative technological leap is required in order to continue extending the capabilities of the device and to continue adding value to the product. This can be illustrated by looking at the evolution of high lift devices with regard to the similarities that Smith [5] points out between the process of boundary layer development on a biplane and that of an airfoil system of two or more slots. A combination of the understanding provided by the determined research of people such as Handley Page and Lachmann, and improved manufacturing processes and more powerful analytical computer programs allowed the innovative leap from a biplane to a mono winged aircraft with deployable high lift system elements.

It has been asserted above, that those traditional mechanically deployed high lift systems have reached the peak of their optimisation. The present day objective is to develop, through the exploration, integration and demonstration of a range of technologies the solid foundations for future aerodynamic concepts and configurations, whilst also considering the manufacturing, design and safety issues, in preparation for the next leap.

A substantial part of low speed, high lift aerodynamics is finding the correct combination of geometry and flow control in order to delay the separation of the boundary layer from the top surface of the airfoil. Flow control technologies applied to the leading edge of an airfoil are far more effective on an airfoil that demonstrates a leading edge separation than on one that demonstrates a trailing edge separation. The ultimate objective of the present work is to use flow control to delay leading edge separation from the airfoil, which in practical terms will allow the removal of the leading edge slat devices.

Current leading edge device technologies. Trends in the aerodynamic theory.

High lift leading edge devices have been the subject of research and development since as far back as 1917 [1]. Handley Page achieved a lift increase of 25% with a span wise slot cut parallel to the leading edge. An improvement in the shape of the slot in a different airfoil produced an increase in lift of 50% [1].



C_L vs. Angle of attack, Dependent upon number of slots.

Figure 2

Woodward and Lean [2] report that until the 1970s and the publication of the landmark work of A.M.O. Smith [5] the aerodynamic community had believed that the slot in Handley Page's wing acted as a boundary layer control device. Smith's classic paper [5] attempts to prove that an airfoil having *n* + 1 elements can develop more lift than one having *n* elements. Using a very highly modified RAF 19 section experimental airfoil he achieved a lift coefficient of 3.92 with 6 slots. This is illustrated in Figure 2, a graph showing the C_L against the angle of attack, dependent upon number of slots.

Smith opposed Prandtl's longstanding idea that the slots were a form of boundary layer control that, "…imparts fresh momentum to the particles in it, which have been slowed down by the action of viscosity…the particles are able to reach the sharp edge without breaking away" [6]. Smith also challenges Lachmann's studies and suggests that in the work described in a paper by Lindfield [7], Lachmann only considered half the problem – the effect of the slat on an airfoil and did not consider the effect of the airfoil on the slat.

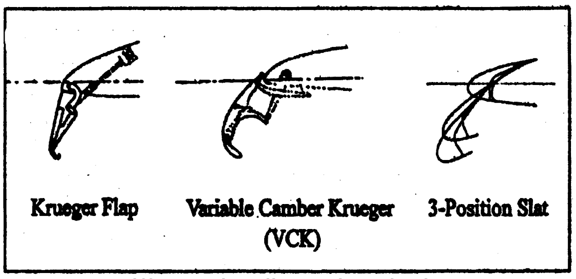
Smith's explanation was that for an airfoil system of two or more elements, so long as there is no merging in the slot, the process of boundary layer development is no different to that on a biplane - subject to their particular pressure distributions the two boundary layers grow, trail off downstream, diffuse and finally merge. In an airfoil system with properly designed and spaced slats, the slats are far enough apart that each element develops its own boundary layer under the influence of the mainstream [5].

Smith spoke of properly designed aerodynamic slots when he summed up the relationships of pressure and velocity between the different elements of a multi-element airfoil into five primary effects. Van Dam paraphrased these in 2002 [8] as: "The circulation of a forward element induces flow on a trailing element counter to the natural acceleration around the leading edge. This so-called (1) *slat effect* reduces the leading edge suction peak on the trailing element, thus reducing pressure recovery demands and delaying separation. The trailing element, however, induces a (2) *circulation effect* on the forward element, which tends to increase the loading on the forward element, increasing the lift, but also increasing pressure recovery demands. Yet, the high velocity flow on the upper surface of the trailing edge of the trailing element allows the flow to leave the forward element at a higher speed. This (3) *dumping effect* reduces the pressure recovery of the forward element and favours (4) *off-surface pressure recovery,* which is more efficient than recovery in contact with a wall. Finally each element has a (5) *fresh boundary layer* that originates on that element. A thin turbulent layer can withstand stronger pressure gradients than a thick one and is less likely to separate. Effectively the overall pressure recovery of the multi-element system is divided among all the elements, but the boundary layer does not continuously grow along the chord as it would if the system was a single element."

In 2002, van Dam points out that the primary viscous effect of gaps is the existence of individual wakes from each element of the system and, in agreement with Smith, the wakes are thought to provide a damping effect on the pressure peak of the trailing elements, reducing the tendency of the flow to separate. Van Dam suggests that the wakes often tend to merge with the boundary layer of the trailing element and the resulting boundary layer is much thicker than an ordinary boundary layer and more likely to separate. His opinion is that optimising the gap size requires a balance between the inviscid and viscous effects, which favour smaller and larger gaps respectively. No doubt the next level of analysis is only possible with the tools that are available to researchers in 2003.

Nose profile.

A droop nose was applied to the leading edge of transonic wing sections to improve the low speed high lift capability by the research team at Hatfield [9]. This had the effect of reducing curvatures from the stagnation region to the point where the suction peak develops at high (low speed) lift coefficients. A "peaky" supersonic flow developed at high speed, slightly further back on the chord. A droop nose can have a dramatic effect on low speed maximum lift. An increase of 11% is claimed to be modest [9]. However, careful design of the droop is required as a suction peak that develops on the lower surface under the "chin" of the droop will go supercritical at low cruise lift coefficients with an associated loss of lift between the upper and lower surface pressure distributions that can be in the order of 1-2% of design lift coefficient [9].



3 Different leading edge devices.

Figure 3

Some typical leading edge devices.

The complexity of high lift systems probably peaked on the Boeing 747, which has a variable camber Krueger flap and triple slotted, inboard and outboard trailing edge flaps. Since then the tendency in high lift has been to achieve higher levels of lift with simpler devices in order to reduce fleet acquisition and maintenance costs [10].

Possible leading edge devices include:

- Hinged leading edge (droop nose),
- Variable camber (VC) leading edge,
- Fixed slot,
- Simple Krueger flap,
- Folding bull-nose Krueger flap,
- Two position slat and three position slat.

Figure 3 illustrates a Krueger flap, a variable camber Krueger flap and a 3-position flap.

Hinged leading edge (droop nose). There is no known use of a hinged leading edge on a commercial subsonic airliner [10]. The local curvature on the wing upper surface is too tight and causes flow separation. On a supersonic airplane with a much higher leading edge sweep angle a stable vortex is triggered on the upper surface that provides lift [10].

Krueger flaps. Simple Krueger and folding bull-nose Krueger flaps are generally designed with the hinge inside the wing leading edge and connected to the panel with a gooseneck hinge fitting. An additional slave link is required to rotate the folding bull nose into the proper deployed position. Actuation can be by a single linear hydraulic actuator, by rotary actuators, or by screw jacks [10].

VC Krueger flaps. VC Krueger flaps require a four-bar linkage as the support mechanism, with additional linkages for flexing the main Krueger panel and deployment of the folding bull-nose [10]. All Krueger flaps deploy against the forces of the airstream and have a high stowing load at low angles of attack. At higher angles of attack Krueger flaps start to produce lift, which causes actuation loads to reverse – an undesirable situation in terms of safety. The actuation loads for Krueger flaps are fairly high and require powerful actuators, which are heavy [10].

Slats. Most slats in service on commercial airliners are mounted on circular arc tracks with two tracks per slat panel [10]. The air loads on a slat are essentially normal to the path of deployment by the circular arc tracks the magnitude of the actuation loads is therefore low [10].

Several different actuator arrangements for slat actuation are used on today's commercial airliners including: hydraulic actuators, rotary actuators with drive links and screw jack drives [10].

Tables 1 to 3 give an indication to the weight and cost of leading edge devices for different aircraft. It is noted that weight comparisons are highly subjective and require careful interpretation.

Boeing		McDonnell Douglas		Airbus	
707	Simple Krueger	DC-8-60/70	3 Position slats	A300	3 Position slats **
727	3 Position slats **	DC-9-10	None	A310	3 Position slats **
737	3 Position slats **	DC-9-30/50	3 Position slats *	A320	3 Position slats ***
747	VC Krueger	MD-80	3 Position slats *	A321	3 Position slats ***
757	3 Position slats *	DC-10	3 Position slats *	A330	3 Position slats ***
767	3 Position slats *	MD-11	3 Position slats *	A340	3 Position slats ***
777	3 Position slats ***		3 Position slats *		
* With slave tracks.		** Inboard, folding bull-nose Krueger.		***Without slave tracks.	

Applications of leading edge devices [10].

Table 1

	Fixed LE	Moving LE	Actuation and controls	Total
LE slat with slave track	1400	1000	300	2700
LE slat without slave track	1100	840	250	2190
Fixed camber Krueger	1000	800	300	2100
VC Krueger	1200	1500	400	3100

Part count for leading edge devices [10].

Table 2

	Slat without slave tracks	Slat with slave tracks	Fixed camber Krueger	VC Krueger
Weight (lb)	2550	2640	2310	2680
Part count	2190	2700	2100	3100
Cost (m$)	0.964	1.142	0.848	1.292
Savings (m$)	0.178	Base	0.304	(0.150)
% LE cost	84	100	74	113
% aeroplane manufacturing cost	2.5	3.0	2.2	3.4

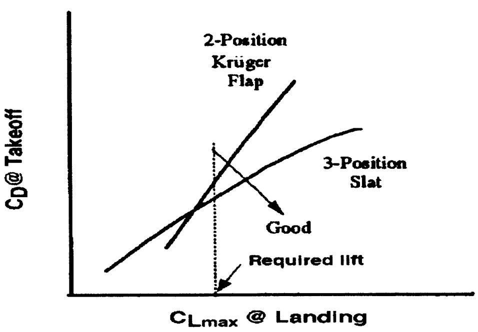
Manufacturing cost for leading edge devices for an aeroplane of 250,000lb maximum [10].

Table 3

Design considerations.

The general objective in high lift system design is to match the airfield performance requirements in terms of approach speed, take off field length and climb rate. Also, maximum flight safety must be guaranteed, which implies good handling qualities, moderate approach speeds and “normal” controllable stall characteristics [11]. The high lift design process involves the basic wing design and the development of target design parameters such as C_{Lmax} and L/D ratio. Increasing the basic wing aspect ratio is beneficial for the high lift efficiency while increasing the wing sweep is disadvantageous [11]. A high wing loading increases the necessary maximum lift capability to satisfy the required airfield performance and hence increases high lift system complexity. Using traditional high lift systems to achieve the aircraft performance required in modern busy airports will increase the high lift system complexity and hence the weight and cost of the product.

If the aircraft is to use a leading edge device, the choice of device will depend on the exact demands required by the design mission. Figure 4 is an example of a trade study for an inboard wing on a twin-engine plane. The optimum device is to provide the minimum take off C_D with a C_{Lmax} sufficiently high enough to meet the approach goal speed and considers a three position slat and a two position Kruger flap [12].



Example of a trade study for an inboard leading edge device.

Figure 4

High Reynolds number windtunnel tests data [12] gathered during the development of the Boeing 777 high lift design showed that during takeoff the slats were ideally sealed against the fixed leading edge and that any amount of gapping increases drag in this configuration [12]. However, this result does not agree with Wedderspoon reporting on the development of the Airbus A320 high lift development [13]. In more recent times, Computational Fluid Dynamics (CFD) codes are used to design the fixed leading edge surface and generate parametric slat positioning data. This comparatively recent use of computing power has increased the optimisation of the slat positioning and further reduced the slat / gap optimisation window.

The location of the engine has an impact on both the C_{Lmax} and on cruise drag. A higher maximum lift coefficient was achieved during the development of the Douglas Aircraft Company DC9 by mounting the engines to the fuselage rather than to the wings. This configuration leaves a clean wing leading edge and a flap uninterrupted by an opening for jet exhaust or nacelles. A reduction in cruise drag results from the elimination of wing-pylon interference [14]. A reduction in wing-pylon interference drag at the higher lift coefficients of the takeoff climb condition gives increased climb performance.

Four failure modes for high lift systems must be considered as part of the design process:

1. Structural failure at high speed,
2. Structural failure at low speed,
3. Failure of the device to be deployed at high speed and
4. Failure into the high-speed configuration at low speed.

Maximum operating loads occur mostly during low speed manoeuvres with the devices deployed. With the exception of flaperons, high lift system components are not control surfaces. However, failure of the system can have serious consequences on the controllability of the aircraft. An important consideration for a safe design, and one that supports the argument against increased complexity is to minimise the probability of failure by minimizing the number of parts and joints in series.

For more than 30 years different aircraft manufacturers have developed different approaches in the development of their high lift systems.

<u>The Douglas Aircraft Company DC-9 (1966).</u>

The aim was a clean leading edge and a configuration that gave the lowest operating cost for a given cruise speed, payload, range and field requirements [14]. To keep the leading edge clean a decision was taken to mount engine on the fuselage [14].

The basis of the DC-9 Series 10 wing was an airfoil developed for the DC-8 that offered high lift capability and excellent high-speed drag characteristics [14]. Douglas was concerned with the deep stall characteristics, which occur at angles of attack between 35° and 50°, in particular, adequate stall warning, strong natural pitch down at the stall for inherent recovery and good lateral control through the stall. The wing was designed to stall first at 35% semi-span, leaving the outer panel and the root unstalled for about 2° beyond the initial stall angle of attack [14]. Varying the shape of the leading edge controlled the maximum lift coefficient across the wing, since the basic airfoil contours were based on high Mach number requirements. Some minor pitch up occurred at the normal stall due to span wise flow causing stall too early on the outer panel. Normal stall is defined as the angle of attack range starting with the angle for maximum lift and extending for between 4° to 6° beyond it. In the deep stall region the pitch down moment was not sufficient to assure positive pitch down capability to the pilot at the aft centre of gravity position [14].

<u>The Airbus Industrie A300B wing – the European Airbus (1973).</u>

The A300B was designed to be a short to medium range turbofan aircraft, with lowest operating costs when operated on stage lengths in the 350 to 500 mile range. Its field performance was to be suitable for major European routes and a "limited" approach speed. Two engines were used and the wing had an aspect ratio of 7.72 and a sweep of 28°. Very high cruising altitudes were not required as economy over short ranges was important and so a high wing loading could be used during the airplane's cruise segment. The combination of high wing loading and limited approach speed meant that as high a C_{Lmax} value as possible could be used. The high lift system was to avoid adverse effects on the take-off climb drag or on high Mach number characteristics [15]. The engine on the A300B was located on the trailing edge "kink" that is required to locate the undercarriage on wings with sweeps in excess of 25° [15].

An attempt was made to combine the "peaky leading edge" concept introduced by Pearcy [15] with the results of the high lift research at Hawker Siddeley, Hatfield during the Trident era, and blend high, low speed C_{Lmax} and a "peaky" high-speed behaviour into one leading edge. The research at Hatfield showed that in order to have a high value of low speed C_{Lmax} with slats extended it was necessary to have airfoil profiles, slats closed, that also had relatively high values of low speed C_{Lmax}.

The slat was essentially continuous across the region of the engine pylon. A small cut out in the leading edge of the slat was provided to clear the engine pylon when the slat was fully extended. This cut out is filled in the clean configuration by a plug that was mounted on the slat and is parked in the low velocity region just behind the slat when the slat is extended [15]. Optimum slat positions in terms of gap, angle and overlap were found from wind tunnel optimisation studies. The aim was to produce a stall that commenced at the most highly loaded section (approximately 75% semi-span). The inboard wing could then be degraded to give an inboard stall. The slat chord distribution across the span was about midway between constant dimensional chord and percentage chord. The slat was to open at a constant angle across the span [15]. The slat taper chosen to achieve the inboard stall was based on experience gained during the development of the Trident 1E.

The Boeing 777 high lift aerodynamic design (1995).

The initial airframe engine combination, known as the 777-200 "A-Market", is sized to replace McDonnell Douglas DC-10s and Lockheed L-1011s on medium range flights (up to 5300 nm). The "B-Market" model employs higher thrust engines to carry more fuel in order to extend the range up to 7,400 nm [16]. The high lift elements were designed using a combination of two-dimensional and three-dimensional codes [16].

The close coupling of the engines to the wing leading edge impacted on the design leading edge device. The inboard slats could not extend to seal against the engine struts so a small Kruger flap was used to fill the hole preventing any drag penalty. The C_{Lmax} was not affected by the hole [16]. A nacelle chine was mounted to the inboard side of the engine cowl to delay inboard stall by producing a strong vortex that compensates for the presence of the nacelle and strut [16].

The 777 wing has a reasonably high aspect ratio (8.42) yet has a relatively large spar box for structural efficiency and fuel volume. This limited the leading edge slats and the trailing edge flaps to chord ratios smaller than any commercial jet transport at that time. The wing tip fairings were raked outboard such that the trailing edge is longer than the leading edge. This provides the lift and drag benefits of span without the cost and weight of extending the leading edge device, even at low speeds [16]. There was a strakelet at the wing root leading edge, which restricts the inboard extent of the leading edge device.

The leading edge of the 777 is fitted with inboard and outboard slats, a Krueger flap inboard of the engine strut and a nacelle chine. A trade study, similar to the one in Figure 4 was carried out in the decision making process in making a choice between slats and Krueger flaps. An early Boeing wing leading edge with a smaller radius had used variable camber Krueger flaps. As the leading edge radius increased slats became the preferred choice [16]. Sculpting the fixed leading edge contour, which is hidden behind the slat in cruise allowing the exterior lines of the slat to be part of the cruise wing, was made more difficult by the relatively small slat chord.

CFD codes were used to design the fixed leading edge surface and to generate parametric slat positioning data. A 2 dimensional code was used to evaluate the different wing leading edge shapes and slat positioning [16]. The effect of the slat trailing edge height above the fixed leading edge height and slat deflection angle was determined at a fixed gap. The desired configuration for the 777 minimised the fixed leading edge suction peak while also minimising a slat wake parameter such as the momentum thickness at the slat trailing edge. This type of evaluation was used in designing candidate slat configurations and as a guide for positioning [16].

Flow control technologies.

This section provides a review of flow control technologies appropriate to control of leading edge separation. Discussion will be limited to technologies that are sufficiently mature for application within 5 years. Flow control technologies can, in general, be divided into those that are passive, active and reactive. An active system can be classified as a system that requires power input and would include traditional high lift systems that require power to deploy devices. Passive systems do not require a power input for their operation, but in general exact a drag penalty during cruise, for example, static vortex generators placed on the leading edge. Reactive systems possess some intelligence and are either predetermined or actuate proportion to the signal that is supplied from the sensor.

Typical aerodynamic flow control goals are:

- To reduce drag,
- Enhance lift,
- Augment the mixing of mass,
- Momentum or energy,
- Suppress flow induced noise, or
- A combination of the above [17].

Ways of achieving these goals for either free-shear or wall-bounded flows include:

- The delay or advancement of transition from laminar to turbulent flow,
- The prevention or provocation of flow separation and
- The suppression or enhancement of turbulence levels [17].

Simple passive devices can be used to extend the stall margin of a wing for low speed, high angle of attack operation. However, the same device will typically increase drag during high speed, low angle of attack operation. If both high speed cruise as well as low speed landing and take off performance have to be performed over a range of wing conditions, active devices are required which can be deployed or activated only when needed [18].

The characteristics of each type of flow control can determine the aerodynamic cost in the design trade off. The criteria upon which the trade offs are based depend upon how the goal is achieved, i.e. delaying or advancing the transition from laminar to turbulent flow, preventing flow separation or provoking flow separation and imposing reattachment [17]. A turbulent boundary layer is more resistant to separation and more lift can be obtained at higher incidence, but there is a higher skin friction drag compared to a laminar boundary layer. Lower skin friction as well as lower flow-induced noise can be achieved if transition from laminar to turbulent flow is delayed. A laminar boundary layer, however, can only support a very small adverse pressure gradient without separation and loss of lift and a subsequent increase in form drag. The principal goal choice, for this review, is lift enhancement with an emphasis on control of flow separation.

The flow control techniques reviewed below aim to delay separation of the boundary layer from the airfoil. They include passive and active devices and are all, or have been, the subject of considerable amounts of research over the last 30 years.

Geometry.

The primary function of a leading edge slat is to suppress the pressure peak that would otherwise be present at the leading edge of an airfoil optimised for cruise when it is operated at a high lift coefficient [19]. Upon removal of the leading edge device the optimal pressure or velocity profile must be a compromise between what is required for each of the different flight phases. Several solutions are available to that compromise. Simply adding a flow control technology to an airfoil designed for cruise would not exploit the benefits of the technique. A solution that has been put forward, as part of the HELIX initiative is an inflatable leading edge,

Inflatable droop nose.

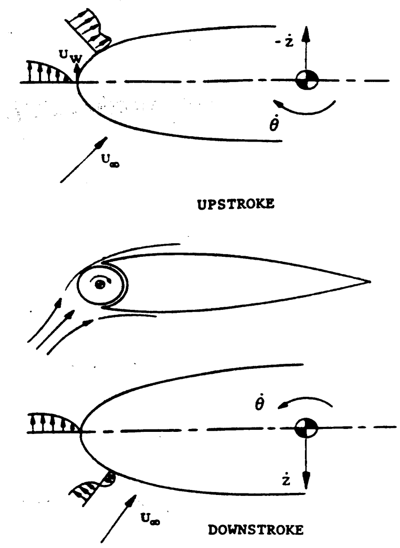
Figure 5

shown in Figure 5 [20]. The inflatable leading edge controls the pressure peak at high incidence angles and deflates to assume the profile of optimised cruise geometry at low angles of incidence.

Moving surface boundary layer control (MSBLC).

The underlying principle behind moving surface boundary layer control is referred to as Magnus lift [21] and has been effectively reviewed by Swanson [22]. The leading edge jet effect of the moving wall can be seen in Figure 6 with a cylinder in place [23]. The Magnus lift is generated mainly by the downstream moving wall effect on the topside moving the separation from the subcritical (laminar) position towards the supercritical (turbulent) position. In the turbulent case the main effect is that of the upstream moving wall on the bottom side promoting separation, moving the separation from the supercritical towards the subcritical position [23].

The MSBLC principle was demonstrated by Goldstein [24] using a rotating cylinder at the



"Leading edge jet" effect

Figure 6

leading edge of a flat plate and Favre [25] used an airfoil with an upper and lower surface formed by a belt moving over two rollers with which he was able to delay separation until the angle of attack, α, reached 55º.

Modi et al. [26] describe the technology as semi-passive in character due to the low power requirements. This definition is actually a further category to those suggested in the introduction. Within the constraints of those categories this technology would be described as active. The cylinders can be hollow and therefore light and, in a steady state, the power requirements are those required overcoming the losses of the bearings supporting the cylinders [27]. Increased manufacturing complexity is due to a wing's span wise chord reduction requiring a cylinder with a diameter that reduced in diameter accordingly.

A further potential design problem was encountered in the wind tunnel. Investigations using combinations of rotating cylinders at various locations around a multi-sectional symmetric Joukowsky airfoil generated vibration problems due to the multi-cylinder configurations operating at high speeds [28].

The importance of the location of the cylinder on the airfoil has been investigated [27].

- A rotating cylinder was used to form an airfoil's leading edge,
- An airfoil with a rotating cylinder leading edge and a plain unslotted flap and
- An airfoil with rotating cylinders at the leading edge of both the airfoil and the flap [27].

The results suggested that there is a critical speed ratio between the cylinder surface velocity (U_C) and the free stream velocity (U) and that the gap size between the cylinder and the airfoil is important. Too large a gap has an adverse effect on the flow [27]. A large unsealed gap would allow communication between the high and low-pressure regions [29]. The presence of the leading edge flap cylinder considerably degenerated the performance as compared to the single cylinder case [27].

When used in conjunction, leading edge and trailing edge cylinders can produce an increase of around 195% in C_{Lmax} [26]. The trailing edge cylinder rotation gives an improvement in the lift coefficient at a given angle of attack, before stall [26]. The drag co-efficient increases directly with the cylinder rotation. The surface roughness of the cylinder has an effect on both the boundary layer control and the control of the drag coefficient. An increase of 210% in the lift co-efficient is associated with the axial splined surface roughness condition compared to the smooth cylinder [26].

Ericsson [23] points out that the moving wall effect on laminar to turbulent transition is quite straightforward. However, when the moving wall effect influences flow separation via the boundary layer transition mechanism, the total moving wall effect becomes much more complicated and, in general, it also has a larger influence on the unsteady aerodynamics than is the case of the purely laminar or turbulent boundary layer separation. In most full-scale flight cases, it is the more complex form of the moving wall effect that has to be dealt with [23].

Hassan and Sankar carried out a purely numerical study of MSBLC [30]. They found that the benefits gained from the introduction of vorticity in the leading edge region tend to decrease with the increase in the flow angle of attack [30]. For separated flows, according to Hassan & Sankar, the early formation of a leading edge shock wave inhibits the beneficiary effects of the additional momentum introduced into the boundary layer through the rotating leading edge. They contend that the accompanying rapid increase in the drag forces does not warrant the use of this device as a means to control the boundary layer at supercritical or perhaps critical onset flow conditions [30]. They argue that previous experiments, [26,27,28,29] mentioned here, although quantitative in nature provide information about the character and behaviour of the boundary layer only in a general sense [30] and the technique is limited to flows that do not contain massive boundary layer separation and is therefore not suitable for the analysis of flows at angles of attack approaching or exceeding the static stall angle [30].

Hassan and Sankar [30] modelled compressible flow past an airfoil with a leading edge rotating cylinder using the full Reynolds averaged Navier-Stokes equations with body fitted curvilinear grid and an implicit finite difference scheme [31]. For realistic values of the Reynolds number this would require significant computer effort and cost. Modi et al. [31] consider the extension of the well-developed panel code to multi-element systems with momentum injection quite sufficient. It is a relevant point that increases in computing power can open up unseen areas for development, particularly as the point of this review is to investigate the flow control technology that holds the most potential for future development. There is, however, a substantial amount of experimental evidence, including that reviewed here [26, 27, 28, 29] to suggest that there is a beneficial change in the L/D ratio associated with moving surface boundary layer control.

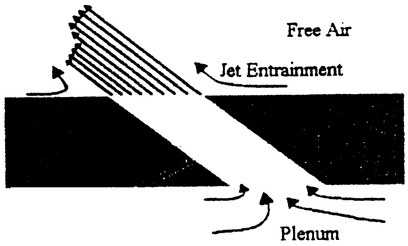
A comparison between the power required by the moving surface boundary layer and that required by a control method with boundary layer suction for increases in C_L and α_{stall} made by Modi et al [31] shows that MSBLC offers more value in terms of the power consumed from the aircraft's system.

<u>Blowing.</u>

Boundary layer control has historically emphasised 3 methods:

1. Blowing,
2. Suction and
3. Vortex generation [32].

The blowing method adds energy to the lower boundary layer by blowing air through slots in the wing surface, energising the flow near the wall and enabling it to overcome a larger pressure gradient [32]. Active transpiration is scarce because of the complexity of the systems and the large power requirements. The airworthiness of the aircraft can be compromised in the event of an engine failure when large power demands are being made for the high lift system. Compensating for the extra power requirements has a spiralling effect on the weight and cost of the aircraft. This technique it is mostly limited to steady blowing in military applications [33].



Jet nozzle.

Figure 7

Jet entrainment had been shown to enhance the lift generated by airfoils [34, 35] and large coherent structures have been shown to enhance the entrainment by effectively transporting momentum across the shear layer [36]. The idea of combining jet entrainment and the generation of large coherent structures as an effective boundary layer control tool was introduced by Seifert et al. in 1993 [33]. Jet entrainment utilizes the phenomenon known as the Coanda effect. Figure 7 shows the jet nozzle. This is the mechanism that allows the jet to remain attached to the curved surface of the trailing edge, even though large directional changes may occur [37]. Superimposing relatively strong oscillations on weak steady blowing provides controlled flexibility. The introduction of periodic motion accelerates and regulates the generation of large coherent structures, particularly when the mean flow is unstable to the imposed periodicity [33].

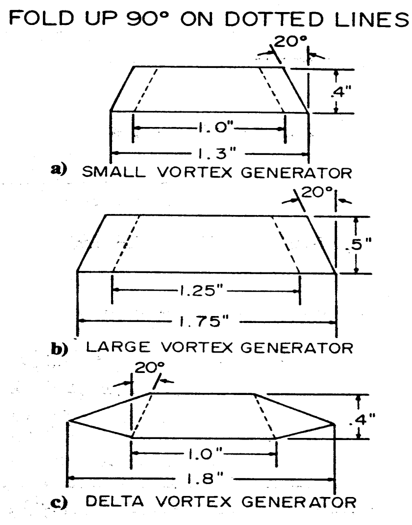
Vortex generators.

Passive vortex generators. Passive vortex generators are essentially small aspect ratio airfoils mounted normal to the lifting surface which introduce vortices into the flow ahead of the separation point to energise the boundary layer and thus to prevent flow separation [38]. Fluid particles with high momentum in the stream direction are swept along helical paths toward the surface to mix with, and to some extent replace the retarded air at the surface [39]. The retarded air, in turn is swept away from the surface. The penalty for energising the boundary layer in this way is drag. Critical considerations include planform shape, section profile and camber, yaw angle, aspect ratio and height with respect to the boundary layer thickness and the spatial relationship of the devices. For instance co-rotating vortices with too close a spacing undergo mutual vorticity cancellation and counter-rotating vortices force large regions of vorticity to rise above the surface and hence are not as efficient as co-rotating devices [40].

Vane type generators were introduced by Taylor [41] and consist of a row of small plates, or airfoils, that project normal to the surface and are set at an angle of incidence to the local flow to produce single trailing vortices [39].

The objective of an experimental study by Bragg and Gregorek [38] was to delay separation in the boundary layer of an airfoil that was subject to early transition due to a contaminated leading edge. The early transition caused the turbulent boundary layer to reach the pressure recovery region with a boundary layer displacement and momentum thickness that is two to four times thicker than in the natural transition case [38]. The vortex generators used are shown in Figure 8. By folding along the dotted lines two generators from each plate are made generating vortices of opposite sign [38]. The small vortex generators were placed chordwise at both 17% and 45% chord [38]. All four configurations increased the lift and reduced the drag on the tripped airfoil. The delta planform caused only minimal drag on the airfoil with natural transition [38].

Wheeler type vortex generators consist of rows of triangular ramp-like devices shaped like overlapping downstream arrowheads [39]. The performance of submerged Wheeler type vortex generators compared to that of conventional vane type vortex generators was investigated by Lin et al. [39].



Vane type vortex generators

Figure 8

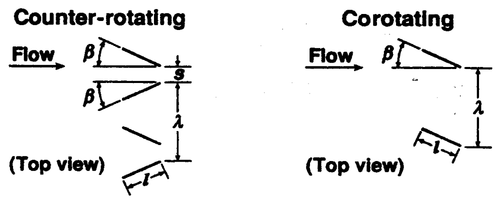
An $h/\delta \approx 0.8$ conventional counter rotating vane type vortex generators, and $h/\delta \approx 0.4$ and $h/\delta \approx 0.1$ Wheeler type devices were compared [39]. The vortex generators were investigated for controlling moderate two-dimensional turbulent separated flow over a backward facing ramp [39]. The Reynolds number for these tests was approximately 9×10^3. The vortex generators were placed at varying distances upstream of the baseline separation. The results showed that the downstream effectiveness of the 0.1δ high

Wheeler vortex required placement of the vortex generator no more than 2δ upstream of the baseline separation line [39].

Further work carried out by Lin et al [42] at higher Reynolds numbers, tested only sub boundary layer height conventional vane type vortex generators as they had been shown to function better than sub boundary layer height Wheeler types in controlling turbulent boundary layer separation [43]. They are also smaller, lighter and relatively easy to manufacture in large quantities at their laboratory site. They tested two types, shown below and are of vane type:

1. A delta-wing with a height to chord ratio of 0.0045 and
2. A trapezoid wing with a height to chord ratio of 0.0018.

Each could be orientated to produce counter rotating or co-rotating vortices pairs [42]. They are shown in Figure 9, along with a comparison between the two different vortex generator shapes [42]. Vortex generators as small as 0.18% chord can effectively control flap separation and that both co and counter rotating stream wise vortices were effective in reducing flow separation [42]. Wishbone Vortex generators with an effective height of three to four boundary layer thicknesses were mounted across the entire span of a trailing edge Gurney flap at 12% chord from the leading



Side view of generator	h	$\frac{h}{c}$	$\frac{l}{h}$	$\frac{s^{\dagger}}{h}$	$\frac{\lambda}{h}$	β
Delta wing	0.10"	0.0045	2.8	1.0	5.0	23°
Trapezoid wing	0.04"	0.0018	7.0	2.5	12.5	23°

†For counter-rotating vortex generators only

Co and counter rotating vortex generator shapes.

Figure 9

edge by Storms and Jang [44] making them partially submerged [44]. The flow separation was delayed from an angle of attack of 12 º to 19º and the lift coefficient increased by 23% [44]. Positioning the vortex generators near the leading edge of the flap such that they are stowed during cruise can reduce the large drag penalty due to the vortex generators [44].

Passive vortex generators delay separation but induce drag. Submerging the vortex generator below the boundary layer reduces the drag penalty. Vortex generators constructed from smart materials and connected to a shear flow sensor were investigated [45] as a way of deploying the vortex generators when they are required and allowing them to lie below the boundary layer when they are not.

Air-jet vortex generators. Air-jet vortex generators have the advantage over fixed vane generators that they can produce strong discrete vortices but have higher momentum cores. They have the potential to be effective in areas where there is separated flow over the airfoil [46] but do not have the associated drag penalty when they are no longer required. The air-jet can be turned on and off as the flow field dictates.

Important parameters include:

- The jet pitch and skew angles,
- Jet nozzle diameter,
- Mach number (or velocity ratio number),
- Ratio of the jet to the free stream value and
- The free stream Mach number [46].

As the diameter of the hole and the Mach number ratio are increased, so the peak vorticity (the value at the centre of the core) rises in a linear relationship with both parameters [46]. Increasing the diameter of the hole and the Mach number ratio, increasing the pressure difference across the jet nozzle increases the mass flow requirement of the jet. These parameters are important as the high pressure bleed air will be provided from the engine air bleed, or from dedicated air-jet system compressor, and thus the vortex generators will need to be optimised based on the air-delivery system [46].

Studies by Selby et al. and Bray [47, 48] have shown that the vortex strength increases with decreasing pitch angle. A pitch angle of 30º gives a good balance between vortex production and manufacturing ease [46]. Jet skew angles of 60º have also been shown to give the optimum result for vortex production [49]. The relative size of the vortex generator is usually expressed as a fraction of the boundary layer thickness [46]. The velocity of the air jet is described relative to the local flow velocity (or Mach number) as a velocity (or Mach number) ratio [46]. Losses come from two major sources:

- Viscous losses at the nozzle wall occurring due to the boundary layer in the nozzle growing with jet nozzle length and
- Separated flows within the jet nozzle [46].

Generally the jet efficiency is a function of jet diameter [46]. Manufacturing issues include sharp edges caused by creating a jet from a circular hole drilled from the plenum chamber cause local separated flows within the jet nozzle. This will further reduce jet efficiency. The design drivers for any air-jet system will be the air-jet mass flow rate and the plenum pressure of the air jet [46]. The jet diameter and the velocity ratio can be set knowing the required strength of the vortex [46].

Acoustic excitation.

Recently attention has been paid to the effect of an imposed sound field on vortex shedding [50]. Parameters of interest include the excitation frequency and the forcing location [50]. Blevins [50] observed that it was not the sound pressure but the velocity induced by sound that influenced the vortex shedding [50] and that the sound induced must exceed the freestream turbulence velocities in order for the sound to influence vortex shedding [50].

For Hsiao et al's. investigations the sound was emanated from the test models from 1mm wide slots at varying percentages of the chord. The slot on a cylinder model was 0.6mm in width and rotating the cylinder [51] could vary its location. A sound pressure level of 95dB(A) was maintained at the slot exit during the experiments.

The effects of the excitation on the lift curve were found to be distinctly characteristic with respect to the angle of attack [51]. When the angle of attack was less than 8º, in the pure stall region, the lift increase is negligible, in the region just prior to stall the lift can be improved by several appropriate excitation frequencies. It can also be determined by several excitation frequencies. In the post stall region, where the angle of attack is greater than 16º a substantial improvement in lift appears [51]. An increase of more than 40% for an angle of attack from 18º - 22º at the excitation frequency near 100 Hz and at an angle of attack of 24º an improvement of 20% [51].

The most effective location is at a position close to the point of separation – especially in the post-stalled region [51]. The most prominent excitation frequency does not change at a fixed Reynolds number at different locations and the effectiveness degenerates as the location moves downstream. The forcing effects are due primarily to the velocity fluctuations around the slot created by the unsteady pulsing of the fluid at the jet exit. [52]. The enhancement of the flow mixing and momentum transport due to internal excitation produces a suction peak on the leading edge of the upper airfoil surface. The suction peak results in an increase of lift and a narrower wake with a smaller velocity defect. Consequently the L/D ratio is improved over a range of angles of attack [51].

Discussion and Conclusions.

Develpoments in current mechanically deployed leading edge high lift systems have reached a level of optimisation where there is a limited amount of room for further optimisation. "Out of the box" thinking is now required to produce an innovative basis which will support the step change onto the next evolutionary "S" curve. The final choice of flow control technology must be an optimum blend of design criteria, manufacturing and operational constraints and aerodynamic advantage. Flow control technology must be integrated into the design of the aircraft at an early stage such that a global optimisation of performance is achieved. A further and equally important point is that when there is a step change away from mechanically deployed leading edge devices then the flow control technology that replaces those devices should have sufficient room for optimisation for the next generation of aircraft.

Summary.

Current leading edge high lift system components and aerodynamic trends have been described. Case studies have been used to give an indication to the leading edge high lift system components selection processes, including trade studies, that aircraft manufacturers use when designing a high lift system to satify the demands of a mission. Tables 2 & 3 showed, for the 3 major aircraft manufacturer featured in the case studies the large number of parts for each leading edge sub-assembly and Table 1 showed how many sub-assemblies were required on a selection of aircraft. Such a large number of parts per wing has implications to the manufacturing process including, longer lead and assembly times, higher inventories, increased manufacturing, operating and capital costs. More complicated systems also become less fail safe without further complexity and become heavier. Traditional high lift systems have, however, reached a point in their evolution where further optimisation will result in further complexity, with a disproportionate increase in value added to the product for the time spent developing the system.

Several flow control technologies have been reviewed that delay separation of the boundary layer from the airfoil surface. Increases in C_{Lmax} of 210% has been cited for the moving surface boundary layer control. The obvious manufacturing difficulties of the technology include manufacturing a cylinder whose diamter tapers at the same rate as the wing's chord changes. Vibration has been raised as a problem for multi-cylinder systems. Further design work is required for this technique in order to allow a wing with a splined cylinder at its nose to cruise without inducing enormous drag. Serious concerns about the technology have been raised by Hassan and Sankar, which have been dismissed by Modi and his colleagues as being the result of having access to computers that are more powerful than are needed for the job! The devil is in the detail, but progressions in the understanding of aerodynamic thoery, from Handley page to Smith to van Dam, have been assisted by more powerful computers and increased computing power has enabled 3 dimensional CFD analysis to reduce design time. It will be interesting to see Hassan and Sankar produce some experimental results.

Steady blowing has been used for a number of years on (older) military aircraft, e.g. the Buccanneer, where C_L values of up to 7 are achieved. Half that value is more than adequate for a subsonic airliner. Blowing is an active flow control technology and as such requires either its own power supply unit or a bleed off the aircraft's power plant. In order not to compromise safety both solutions have weight and cost implications. Acoustic excitation has similar manufacturing issues as blowing. The sound emanates from slots in the upper wing surface. Those slots need to be manufactured and linked to the source of the sound pressure.

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