Systems and certification issues for civil transport aircraft flow control systems

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ABSTRACT

The use of flow control (FC) technology on civil transport aircraft is seen as a potential means of providing a step change in aerodynamic performance in the 2020 time frame. There has been extensive research into the flow physics associated with FC. This paper focuses on developing an understanding of the costs and design drivers associated with the systems needed and certification. The research method adopted is based on three research strands:

1. Study of the historical development of other disruptive technologies for civil transport aircraft,
2. Analysis of the impact of legal and commercial requirements, and
3. Technological foresight based on technology trends for aircraft currently under development.

Fly by wire and composite materials are identified as two historical examples of successful implementation of disruptive new technology. Both took decades to develop, and were initially developed for military markets. The most widely studied technology similar to FC is identified as laminar flow control. Despite more than six decades of research and arguably successful operational demonstration in the 1990s this has not been successfully transitioned to commercial products. Significant future challenges are identified in cost effective provision of the additional systems required for environmental protection and in service monitoring of FC systems particularly where multiple distributed actuators are envisaged. FC generated noise is also seen as a significant challenge. Additional complexity introduced by FC systems must also be balanced by the commercial imperative of dispatch reliability, which may impose more stringent constraints than legal (certification) requirements. It is proposed that a key driver for future successful application of FC is the likely availability of significant electrical power generation on 787 aircraft forwards. This increases the competitiveness of electrically driven FC systems compared with those using engine bleed air. At the current rate of progress it is unlikely FC will make a contribution to the next generation of single-aisle aircraft due to enter service in 2015. In the longer term, there needs to be significant movement across a broad range of systems technologies before the aerodynamic benefits of FC can be exploited.

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NOMENCLATURE

ACARE	Advisory Council for Aeronautics Research in Europe
APU	auxiliary power unit
CFD	computational fluid dynamics
CTA	commercial transport aircraft
D	drag
DOC	direct operating costs
EAP	electro-active polymer
EASA	European Aviation Safety Agency
EEF	electrical-electromagnetic-fluidic
EIS	entry into service
EMF(A)	electro-mechanical fluidic (actuator)
ETOPS	extended range twin engined operations
FADEC	full authority digital engine control
FBW	fly-by-wire
FC	flow control
(H)(N)LFC	(hybrid)(natural) laminar flow control
HTP	horizontal tailplane
L	lift
M	Mach number
PZT	polychrystalline piezoceramic
RAT	ram air turbine
RPK	revenue passenger kilometer
SJA	synthetic jet actuator
(V)VG	(vane) vortex generator

1.0 INTRODUCTION

The aim of the work presented in this paper is to understand some of the legal, commercial and technological constraints affecting the successful application of flow control (FC) technologies on civil transport aircraft, and the likely timescales for deployment. The work is intended to be complementary to the significant scientific literature concerned with understanding the flow physics associated with FC. In the terms given by Bushnell[1], assuming that a flow control technology passes the technical filter, i.e. it can be shown to achieve a threshold level of effectiveness, the next step is to demonstrate that the technology passes the technological filter, i.e. can it be implemented in a cost effective manner that meets the wider social, legal and commercial constraints. Success at the technical filter stage is no guarantee of success at the technological filter stage. While it may be impractical to consider all the technological constraints at the early stages of technical development, acknowledgement of the key constraints helps to focus on technologies that have some chance of succeeding in the short term, and guides the longer term research on more speculative technologies.

The successful application of FC on civil transport aircraft requires input from a significant range of disciplines and it has been necessary to focus effort on a limited set of technologies and constraints in order to make useful progress. The terms of reference for this work are as follows:

1. Research method: evidence to inform the discussion is based on historical analysis of civil transport aircraft technological development in response to changes in the legal, commercial and technical environment in which the design takes place.
2. FC application area: primarily separation control.
3. Cost: the study focuses on the systems cost of implementing technologies rather than aerodynamic benefits.
4. Time frame: FC technologies considered must be suitable for 2020 entry into service (EIS).
5. Legal: Assume that future FC systems will be certificated using the current legal framework (but identify where this might change in response to radical changes in technology).

This next section considers the regulatory and competitive environment for application of FC. The development of new civil transport aircraft has traditionally been driven by the ability of new technology to generate business benefits compared to aircraft of previous generations. However, increasingly stringent regulation for the allowable environmental impact of civil transport aircraft will become a major driver of the configuration of such designs in the future. Evidence for this can be found in documents including the European Union (EU) Advisory council for aeronautics research in Europe (ACARE) targets, demanding large reductions in fuel burn, emissions and noise for civil transport aircraft built in the 2020 timeframe[2].

In seeking to address these targets, a possible response is to continue to refine current technologies and configurations. At the current rate of development of existing technologies, it is clear that the aerodynamic targets specified will not be achieved[3]. This leads to the conclusion that new technologies that can deliver a step change in performance are required. This argument is often used as justification for investment in FC research and it is reasonable to do so. However, it should be borne in mind that unless targets become legal requirements, there is little incentive for manufacturers to comply as the least cost solution is to do nothing, assuming the competition also does nothing. This will be expanded further later in the paper.

In the cruise portion of the flight profile, it is clear from the Breguet range equation that improvement in the range parameter, M.L/D and propulsive efficiency contribute to the fuel burn and emissions targets[4]. This paper is focused on FC separation control and hence is mainly concerned with technologies that can improve aerodynamic efficiency in the off-design portions of the flight. This impacts on overall efficiency primarily by allowing the same cruise efficiency to be achieved at reduced aircraft empty weight; though there may also be some additional cruise drag benefits due to reduction in excrescence drag attributed to the high lift system.

In terms of noise, it is apparent that local flow separations are a dominant source in the landing phase. For example, an experimental study conducted for the Bombardier CRJ-700 regional jet identified the most significant sources of noise in the landing configuration[5]. Of the ten most significant sources, five were directly attributable to the high-lift system, and it was noted that both increased incidence and device deflection resulted in increased noise. These factors could be directly addressed by the technologies discussed subsequently.

1.1 Flow control

Attention will now be focussed on technological issues associated with flow control. For the present work, flow control is defined as: 'The modification of local flow parameters without external geometric change'.

Consider now how flow control buys its way onto an aircraft. By its nature, flow control technology is additive in that it generally requires additional systems and structures that currently do not exist on civil transport aircraft. This will typically lead to additional design, manufacturing and operating costs specific to the use of the flow control, which must be offset by improved aerodynamic performance and/or cost reduction in other systems such that the overall performance/cost ratio is improved. Improvement in absolute aerodynamic performance of a given geometry is often stated as a flow control goal; however, in practice this is very difficult to achieve in the context of highly mature geometric designs. One area where this approach is applicable is the use of laminar flow control for cruise drag reduction. Here, it is possible to achieve absolute improvements in L/D that are not achievable through geometric means alone. The alternative strategy for increasing value is to maintain the same performance but to reduce overall cost by eliminating cost in other systems. This approach is less direct, but there are arguably many more applications where it can be used. A good example is the use of flow control to reduce the cost to delta C_L ratio

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Table 1
SWOT analysis for flow control

Strengths

- Able to achieve absolute improvement in aerodynamic performance not achievable by geometric design alone
- Creates new opportunities for multi design point optimisation, e.g. improved off design performance for cruise-optimised designs

Weaknesses

- Hard to achieve both high effectiveness and high efficiency at acceptable cost
- Difficult and hence costly and risky to design using current industry design tools (significant difficulty/expense in assessing complete system benefits)
- Introduces increased complexity and hence increased cost associated with achieving required levels of safety

Opportunities

- Development of more competitive products with attendant increase in market share
- Product differentiation

Threats

- Successful implementation by one manufacturer could lead to significant loss of market share for those that did not invest
- Unsuccessful implementation could put a manufacturer out of business

for high lift systems through control of separation, e.g. by enabling the use of relaxed geometric tolerances on flap gaps, by allowing of reduced flap chord/greater flap deflections/reduction in number of flap elements, and potentially by elimination of leading edge high lift devices. These will be discussed further below. Another example of a 'cost reduction' as opposed to performance enhancement application is that of use of flow control for noise reduction, e.g. suppression of broad band noise from the undercarriage.

In addition to the costs discussed above, the impact of FC on safety must also be considered, as the cost of achieving and demonstrating the required levels of safety are significant. Flight systems are often divided into those that are essential to continued safe flight of the aircraft and those that are desirable. For example, the aircraft primary flight controls e.g. elevator, rudder and aileron are considered essential, whereas the secondary flight controls, e.g. ground only spoilers and thrust reverser are considered desirable. It is usual to consider two main failure states: unavailable; and malfunctioning. The level of risk associated with these failure modes depends on the flow control system application. For LFC, system unavailability or malfunction would cause a reduction in the achievable range of the aircraft, which could potentially require a diversion. For high lift system applications, unavailability would cause a reduction in field performance and reduction in safety margins, whereas asymmetric malfunction is likely to be catastrophic. This latter case is avoided by robust monitoring of flap position. The equivalent safeguards for an FC-enhanced high lift system are not so easily defined, and will be discussed later in the paper. Some of the potential issues associated with flow control are summarised using the SWOT analysis shown in Table 1.

The incorporation of FC systems in civil transport aircraft must be consistent with the requirement for certification under the relevant regulations, for example EASA CS-25[6] in Europe or the corresponding FAA regulations in the USA. Major changes in the philosophy of aircraft design and operation have historically been accommodated by changes to the regulatory framework, where these have been shown to provide an equivalent or greater level of safety.

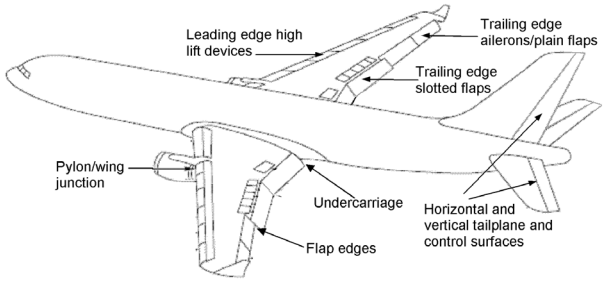


Figure 1. Illustration of flow control opportunities on a typical civil transport aircraft.

Examples of such technological changes could include digital fly-by-wire systems and the introduction of ETOPS operations. Both of these innovations involved changes to established procedures (with associated cost), although both have demonstrated their worth subsequently through efficiency and/or safety improvements. It is notable that the in-service use of LFC has been addressed by both analysis and representative flight vehicle testing[7]. However despite the plethora of laboratory based work on active flow control, little similar work relating to these technologies has been documented.

When discussing the requirements for safety and certification, the likely applications of FC devices must be considered. Opportunities that have been considered in the literature for FC on a typical civil transport aircraft are illustrated in . In summary, these are:

- Augmentation of high lift system effectiveness
- Augmentation of control surfaces effectiveness
- Reduction of noise attributable to undercarriage
- Local flow modification for areas including flap slide edges and wing/pylon junctions

In the off-design portions of the flight mission, civil transport aircraft use complicated and heavy high-lift systems in order to provide the required performance. It has been estimated that these systems typically account for 6%-11% of the aircraft manufacturing cost and contribute a mass penalty of the order of several tonnes[8]. Green showed that the reduction of operating empty weight by a given percentage produces a similar percentage improvement in fuel burn per seat kilometre for medium range (Range~4,000km) aircraft, with the benefit rising further for long range aircraft[9]. There is then significant potential for FC technology to contribute towards improvements in fuel burn and in turn to meeting the ACARE targets, by allowing high lift systems with a lower weight penalty for a fixed effectiveness. This would be achieved by controlling the flow separations that typically occur on the trailing edge flaps, allowing increases in allowable deflection and hence performance[10].

When future aircraft designs are considered, the economic and environmental drivers described previously may lead to the adoption of some form of laminar flow control for skin friction drag reduction in the cruise. Like all flow control systems, the full benefits can only be achieved on an aircraft designed from the start with these systems included. Upper surface hybrid laminar flow control (HLFC) can be assumed to be the most likely implementation strategy, given that the required wing sweep for cruise Mach number is likely to rule out natural LFC (NLFC), and that the structural penalty and maintenance requirements are much reduced for only a small performance penalty when compared to implementing HLFC on both upper and lower surfaces[11]. One study has suggested fuel savings of 10% for a conventional design incorporating HLFC, rising to 15% for an aircraft optimised to take account of the technology[12]. Devices for separation control in the cruise would be unlikely to find an application on a geometrically optimised LFC wing, whereas high-lift (or

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leading edge shroud) augmentation may well be an enabling technology that allows the performance benefit to be realised through a wing highly optimised for cruise. It should be further noted that a reduction in skin friction drag may lead to optimised configurations featuring lower wing loadings than are current, which reduces the required lift coefficient increment for high-lift. This may also be a driver towards using less complex high lift systems augmented where appropriate by FC.

Aerodynamic augmentation of flight control surfaces may be considered to be an intermittent application, as the FC systems would be required to operate for only for short periods at a time. In common with high lift system augmentation, the remaining applications are likely to be useful during the low speed portions of the flight. Flow control is therefore most likely to be used in the off design, low speed portions of the flight. It appears to be mainly applicable to the augmentation of high lift systems and some other niche flow separation applications, possibly including undercarriage members. Flow control system operation may also be used to augment control surfaces when deployed during all flight phases.

2.0 THEORY: FLOW CONTROL TECHNOLOGIES

2.1 Active flow control taxonomy

In order to better understand the systems and certification costs of FC technologies it is useful to define a technology taxonomy based on the attributes of transduction, topology and mechanism. Transduction is the process by which energy is transformed from the form with which it is supplied to the actuator into fluidic energy delivered into the external flow. Topology refers to the geometry of the interface between the flow control actuation and the external flow, e.g. holes, slots or surfaces, and mechanism refers to the nature of the interaction between the flow control inputs and the external flow, e.g. enhanced boundary layer mixing through injection of streamwise vorticity, separation delay by unsteady shear layer excitation. From a systems and certification point of view the two most important attributes are transduction and topology. Transduction choice has a significant impact on the power systems needed for implementation, whereas topology (holes/slots) may have a greater impact on environmental protection and structural integration.

For civil transport aircraft the energy transduction path starts with the conversion of chemical energy in the fuel to heat energy and then rotational mechanical energy in the engine. This mechanical energy can then be used to either drive a compressor to produce compressed air that can be bled from the engine, or used to drive a generator to produce electrical power. Compressed air can be fed directly to the actuators to provide the necessary fluid power at the actuator output. Electrical power on the other hand needs to be converted back into fluid power within the actuator by an additional transduction step. The engine bleed solution is the simplest since compressed air bleed is typically already available on engines for other purposes. Bleed based flow control has been proposed as a design solution[8] and successfully deployed on several military aircraft since the 1950s[14], and has been proposed for use (but not actually deployed) on a number of civil aircraft[10].

Early flow control applications were typically based on the use of tangential momentum injection for boundary layer separation control on high lift elements[14]. These systems tend to be very effective, i.e. large changes in maximum lift coefficient can be obtained, however significant power off take from the engine is required. This presents issues in terms of the increase in engine weight associated with provision of additional power, and the additional consequences associated with engine failure. Engine bleed can also be used to directly power air jet vortex generator or pulsed slot blowing schemes.

As electrical systems and electrical actuator technology has improved, concepts for electrically powered flow control devices have emerged. The two main electrical to fluidic transduction mechanisms are electrical-mechanical-fluidic (EMF) and electrical-electromagnetic-fluidic (EEF). The most common form of EMF actuator (EMFA) is the synthetic jet actuator (SJA) which has been widely studied in recent years[15-17]. These devices use an oscillating mechanical element in a cavity to produce a net momentum flux in an external flow by a process similar to acoustic streaming. Current generation SJAs driven by commercial polychrystalline piezoceramic (PZT) diaphragms can achieve useful levels of effectiveness, e.g.150ms^{-1}, with an electrical to fluidic power conversion efficiency of around 10%. Polychrystalline PZT has an electrical to mechanical energy conversion efficiency of around 40%, whereas single crystal PZT has an equivalent efficiency of 80%[18]. Thus it could be expected that device efficiency could be doubled by use of bespoke single crystal PZT diaphragms in the existing actuator designs. Peak efficiency occurs at output velocities less than the peak value; maximum measured power efficiency for existing designs is around 15%.

As an alternative configuration, the oscillating mechanical element can be a flexible part of the wetted surface, leading to concept of an active dimple[19] for circular elements, or transition control actuator for strip elements[20]. Synthetic jet devices by definition require an orifice to interface a cavity with the outer flow, and this presents environmental protection challenges. These will be discussed in Section 4.1.1 below. Active surface actuators remove the need for an orifice and cavity; however, as a result there is a significant challenge in impedance matching at the actuator-air interface, typically limiting the peak velocity amplitudes achievable, e.g. a few metres per second and leading to poor actuator efficiency. Note that for some applications such as transition control the required actuator velocity may only be a few metres per second even at cruise Mach numbers so the limited effectiveness of integral surface devices in absolute terms may not be an issue.

Electrical-electromagnetic-fluidic devices are more commonly referred to as plasma actuators. These devices produce fluidic actuation by ionisation and subsequent electromagnetic acceleration of the air local to the actuator. This transduction process tend to be very inefficient, e.g. less than 0·1% electrical to fluidic energy conversion efficiency, with most of the supplied energy ending up as heat as a result of the ionisation process rather than fluidic kinetic energy, and the effectiveness is relatively low, e.g. peak velocities of the order of a few metres per second. There are also electrical system issues associated with the need for very high voltage (up to 10s of kilovolts) power supplies. Plasma actuators, do however , have a unique advantage in that transduction process requires no moving parts, which is a significant advantage from a maintenance point of view. For a recent review of the literature on plasma systems the reader is referred to a review by Moreau[21].

While the discussion in this paper is intended to cover all flow control technologies, significant attention will be given to electrically powered actuators rather than those that are pneumatically powered via engine bleed. There are two main reasons for this:

1. For reasons of overall efficiency, future civil aircraft systems architectures are increasingly based on electric rather than pneumatic systems, Electrically powered flow control systems will therefore offer the potential for greater synergy with the systems on future aircraft.
2. Electrical systems have particular requirements that have not been addressed in the research literature to date. In contrast, many of the issues associated with pneumatic systems have been extensively discussed in relation to boundary layer control and laminar flow control systems.

With regard to the types of electrically powered flow control actuator that are likely to see service in the 2020 time frame, it would seem that some form of EMFA in the form of SJA is a practical option given sufficient development. In light of this, the

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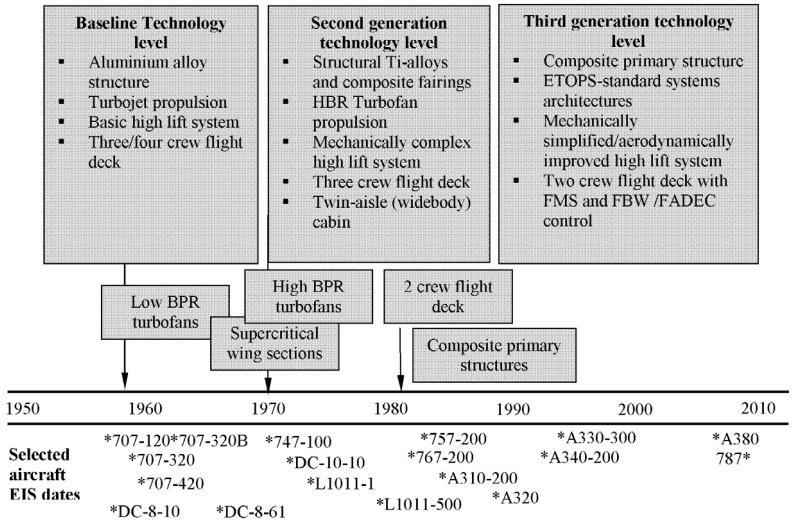


Figure 2. Illustration of some significant points in the development of civil transport aircraft technology.

discussion in the rest of the paper is in many places biased towards discussion of EMFAs (and specifically SJAs) rather than active surface or plasma actuators, or any of the direct pneumatic actuator technologies.

Gomes *et al*[22] have conducted a study on the system impact of EMFA systems (in this case an SJA based approach) on the wing of a representative single aisle civil transport aircraft. These authors concluded that the use of SJAs to replace VVGs for cruise shock control was both the most costly and the highest technical risk wing application, based on the disparity between the peak velocities required (M~1·0) and those achieved to date (M~0·5). This velocity requirement stems from the high flow local velocities and thus power offtake required to provide a viable velocity ratio, when at cruise speeds. Augmentation of the high-lift system appeared more attractive for these reasons, together with the significant difference that operation would be for a small proportion of the flight only. For short period or intermittent operation, these authors found that the provision of power was the major driver for system mass; for cruise applications the mass of fuel (i.e. energy into the system) became much more significant.

Other possible EMFA applications have been considered. Liddle[23] studied the application of these devices to augment ailerons; other flight control surfaces could also benefit. The replacement of double-hinged rudders and reduction in/elimination of the requirement for horizontal tailplane (HTP) incidence control are examples of other weight saving opportunities. Aside from pure separation control, the modification of the local flow around an undercarriage member using EMFAs for the purposes of noise reduction is being investigated[24].

3.0 HISTORICAL REVIEW OF THE APPLICATION OF DISRUPTIVE TECHNOLOGIES TO COMMERCIAL TRANSPORT AIRCRAFT AND LESSONS APPLICABLE TO FC

3.1 Development of civil transport aircraft and associated technologies

The aim of this section is to discuss the likely engineering requirements and timescale for the introduction of active flow control technology on civil aircraft. In assessing these requirements, it is useful to consider the development of civil transport aircraft and how new technology has previously been incorporated.

The research method adopted is to:

1. Review the development of the civil transport aircraft from the beginning of the gas-turbine era
2. Review the implementation strategies for previous new technologies, both successfully and unsuccessfully implemented.
3. Discuss the legal and technical issues pertinent to the implementation of flow control in the light of the historical review and the requirements of the certification process.

Figure 2 gives an overview of some of the technologies that have been incorporated in civil aircraft since the introduction of the gas turbine-powered transport. Three technological generations have been identified as baseline, second generation and third generation based on technological breakpoints associated with the introduction of new aircraft types by the manufacturers.

The baseline technology level is taken to be that of the Boeing 707, which entered service in 1958. Notably this was not the first jet transport, but it was the first to be widely used and its configuration became dominant. The earlier Comet was built in small numbers and was rapidly displaced by the 707 and DC-8, its configuration not being repeated by later types.

The second generation technology level is typified by the first widebody aircraft: Boeing 747, McDonnell Douglas DC-10 and Lockheed L1011 TriStar. The key enabling technology was the high-bypass ratio turbofan engine. This technology reduced thrust specific fuel consumption from ~23gkN^{-1}h^{-1} (JT-3D) to ~18gkN^{-1}h^{-1} (JT-9D), representing approximately a 22% reduction. From the Breguet range equation, it is clear that a 'snowball' effect exists, as a reduction in fuel consumption means that less fuel needs to be carried, further reducing both fuel and structural mass.

The third generation of aircraft is typified by the Airbus A320 series. With the 'quick gain' of the step from low- to high-bypass ratio already in place, further improvements in fuel consumption associated with the propulsion system were achieved by several other means associated with new materials and improved internal aerodynamics. New materials and manufacturing processes allowed increases in turbine inlet temperature, the incorporation of wide-chord fan blades and reductions in parts count. On the other hand, turbomachinery aerodynamics benefited from rapid developments in CFD[25] capability during the period. Moving to the airframe, composites were used for primary structure for the first time, allowing a reduction in mass compared to previous generations using all metallic primary structure. Major reductions in direct operating

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cost (DOC) were achieved by changes in systems architecture and operating procedures. These changes included improved avionic systems that enabled elimination of the third crew member and improved navigation; Fly-by-wire (FBW) and full authority digital engine control (FADEC) technology that enabled reduced maintenance costs and improved cruise efficiency; and regulatory changes that drove the development of systems that enable extended range operations by twin engined aircraft (ETOPS). The latest aircraft to be produced, for example the Airbus A380 and Boeing 787, have continued these trends and may be considered as generation 3.5.

Consideration will now be given to the drivers for technology change in this sector. Civil transport aircraft are produced to meet a perceived market need, with the aim (in general) of producing a profit for the manufacturer. Advanced technology is used to produce aircraft that may be more effective (able to exceed the baseline performance) or more efficient (able to achieve a specified performance level at a lower cost) than those currently in service, thus allowing the new type to exploit new markets or supplant existing products at its service entry.

It is clear that the main driver for the introduction of new aircraft is to reduce costs for the customer. The costs of operation of an aircraft are usually considered in terms of revenue passenger kilometre (RPK) cost (the cost of transporting one passenger for one kilometre) or direct operating (DOC) cost (cost resulting from operation of the aircraft in service). The promise of a significant change in these parameters is a pre-requisite for the development of a new aircraft as opposed to an upgrade of an existing type.

A major driver for change is the ability to incorporate a proven technology developed outside the commercial concerns of civil aerospace. Employing a proven military technology is a key risk reduction method for new aircraft. The obvious example of this is the adoption of the high bypass ratio turbofan, as described above. This technology was developed for (and funded by) the requirements of the USAF CX-HLS competition. The requirements of supersonic flight forced the development of new technology or adaptation of military technology for supersonic transport aircraft. These technologies, including materials advances, were then available to support new CTA programmes.

On occasion, development has been forced by changes in legislation, which may or may not be to the benefit of either manufacturer or customer. Changes in noise legislation have on several occasions caused the retirement of older types and the development of new. The ability to fly ETOPS operations (a legislative change) altered the economics of operating three- and four-engined aircraft, relative to equivalent twin engined aircraft. In general terms, the cost of additional systems required for ETOPS certification of twin-engined aircraft were outweighed by the lower DOC associated with a reduction in the number of engines.

The requirement to introduce a completely new aircraft is connected to the economic lifetime of current types. There is evidence that customers are reluctant to replace aircraft as they become life expired with essentially the same type, as the large investment may be perceived to be in old technologyxxvi. This provides an incentive for new development, either by upgrade if this can produce the required change in economics and the potential exists in the design, or by new type introduction. An example of the former is the development of Boeing 747-400 from Boeing 747-200, with the incorporation of third generation technology in a second generation design.

The push to introduce new technology to reduce cost appears to be counteracted by several factors. As the development time of a completely new aircraft type is typically of the order of a decade, the ability to accurately predict both the technology state and economic conditions at the time of service entry is difficult. A major driver towards conservatism is the risk associated with use of new technologies, considered alongside the need to extend the production runs of current aircraft as long as possible to give maximum return on investment. Indeed, the dynamics of the market suggest that producing an aircraft with too great an advantage over a competitor inevitably causes that competitor to produce a new type or upgrade that erodes that advantage. The profit to be derived from this change to the manufacturers following the development cost may be significantly less than if the original types had been kept in production, although the airline customers would receive more effective or efficient products for their fleets. Postponement obsolescence may therefore be practiced in order to extend production runs before a replacement is introduced. Boeing for example had considered FBW, composite construction and Propfan propulsion for a new 150-seat aircraft termed 7J7[27], for entry into service in 1992. However, the competitive environment meant that continued development of the then current 737 in this market sector appeared more viable overall, despite the promise of improved fuel efficiency from the new aircraft.

The phenomenon of technology lock in can also provide a dampening effect on development. The introduction of a new aircraft type to both the global and individual operator fleet has an associated cost. If an older type is replaced, the support infrastructure will also need to be replaced. A new type may incur higher support costs with maintenance, repair and overhaul (MRO) organisations, which is countered by the improving reliability of newer systems. More widely, the operational infrastructure including airports provides constraints on the design of new aircraft that can reduce performance. An example is the restriction in span and thus aspect ratio of the Airbus A380.

It must be noted that while estimates of the improvement in RPK or DOC achieved by aircraft due to the incorporation of new technologies can be made, the accuracy of these estimates is open to question due to the sensitive nature of the input data.

3.2 Timelines for FBW and composites

It is logical to consider historical technological innovations in order to assess the likely timescale to implementation for active flow control systems. It has been stated that 10-15 years can be expected to elapse for new technologies to transfer from laboratory to production level in the civil aerospace sector[28]. The timescale from demonstration to development of two technologies now in widespread use in civil transport aircraft, digital fly-by-wire flight control systems and structural composite materials, is illustrated in . In the case of digital FBW, the major advantages over conventional systems have been summarised as[29]:

- reduced cost of increased redundancy
- reduced weight
- easier separation of power/control channels
- improved performance
- feasibility of incorporating advanced automated control features
- Less susceptibility to failure (robustness) should the aircraft incur physical damage

The first flight tests took place as part of a NASA programme using a modified F-8C aircraft in 1972. It was however not until the entry into service of the Airbus A320 in 1988 that this technology was implemented in a civil application, a development period from first flight test of 16 years. Since the A320, every new 100+ seat civil transport aircraft design has used digital FBW technology.

A similarly long development and proving period has been required for the use of composite materials for structural components. An incremental path is evident, ranging from use in secondary structures such as tailplane leading edges in the early 1970s, through to full tailplane primary structures in the 1980s. The Boeing 787 will be the first civil aircraft to feature a composite fuselage, suggesting that confidence to use the technology to its full potential has only been reached over 30 years after its service introduction.

Both of these technologies were in use in military aircraft in advance of their civil introduction. This enabled some of the

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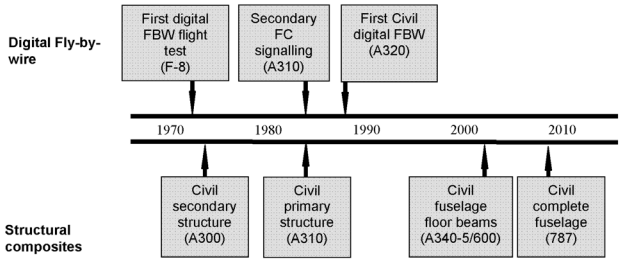


Figure 3. Selected milestones in the development and use of two aerospace technologies in civil transport aircraft, digital fly-by-wire (FBW) and structural composite materials.

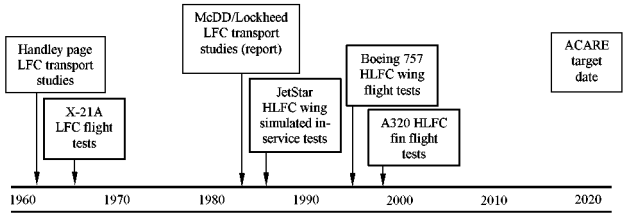


Figure 4. Timeline of LFC development.

research and development, in both concept and implementation to be undertaken with less commercial risk. For example the AV-8B aircraft, which made its first flight in 1981 featured a complete composite wing, while predominantly composite structures were evident in combat aircraft entering production in the mid- to late 1990s.

3.3 Laminar flow control

Development of laminar flow control technology for civil transport aircraft has been carried out over many years. Some of the major events are illustrated in Fig. 4. It may be noted that while the first event indicated is in 1961, LFC has not yet been implemented in a production civil transport aircraft.

Successful proof-of-concept flight tests with a suction based system occurred in the early 1960s using a modified B-66 aircraft, the X-21A[30]. Simulated airline service of a hybrid laminar flow control (HLFC) system was carried out using a modified Lockheed JetStar aircraft in 1985-86. In the intervening period between these tests, problems encountered on the X-21 of insect contamination and cleanliness were addressed by using a purging system, deicing fluid and/or a Kruger type leading edge shield[31]. The programme was considered successful in that LFC performance was maintained while operating the aircraft in a similar fashion to that of the intended production application. More fundamentally, the lesson was learned that while the flow control system was undoubtedly complex, it proved possible to maintain and operate such a system in service, albeit simulated.

Some of the innovations incorporated in the JetStar test, including the systems and manufacturing techniques, were developed during a NASA sponsored study in the late 1970s and early 1980s. To a large extent, the manufacturing and structural systems developed made the difference between an expensive test vehicle and a viable in-service approach. The X-21A proved difficult to operate due to problems in maintaining the surface quality of the actuated wing, which was equipped with an arrangement of narrow slots. By contrast, the use of manufacturing techniques such as laser drilling to produce porous skin panels enabled a wetted surface to be created that required significantly less attention between flights.

The above study culminated in reports from McDonald Douglas[11] and Lockheed[32] on the design of a 1995-timeframe long range civil transport (in the MD-11/A340 class), making optimum use of LFC technology. The size of such aircraft coupled with required operating speeds, results in operation in a Reynolds number regime higher than that at which natural laminar flow can be sustained. Taking the McDonald Douglas study, the LFC aircraft was compared with an advanced 'turbulent aircraft' concept of the same technology standard. The LFC aircraft was projected to save at least 16% in fuel consumption and 8% on direct operating costs, with the first cost being only 2% greater.

It is interesting to note that by the 1990s, LFC had been demonstrated in comprehensive design trade studies and in successful flight test. Here was a technology that potentially offered double-digit fuel consumption savings at the then-current technology level, however it was not then (and still has not been) implemented.

There are several reasons why this may be so. The viability of any fuel saving technology is logically affected by fuel price. Real term oil prices rose in the 1970s following the OPEC crisis and peaked in 1979. It could be concluded that this was a driver in the commissioning of these LFC studies. However, as fuel prices fell in the 1980s it became a lower proportion of direct operating costs, and thus the risks associated with LFC would have made the technology less attractive when compared to incremental improvements in, for example, engine technology and turbulent wing aerodynamic design. A similar fate befell the attempts in the late 1980s to introduce unducted fan engines (propfans). The projected fuel savings became less important in a time of falling oil prices, when compared to the risk associated with solving the engineering problems of uncontained fan blade separation and noise.

3.4 Section summary

New technologies have historically been incorporated in civil transport aircraft in order to reduce RPK and DOC, or to allow new capabilities. This development process is governed by factors including:

Driving effects:

- improved RPK/DOC
- requirement for new fleet
- changes in legislation
- increases in fuel price

Retarding effects:

- cost of new aircraft development programs
- cost/uncertainty of new technology implementation
- Increased profit/reduced first cost from extended production runs
- technology lock in
- cost of fleet substitution
- steady fuel price

The implication of the retarding effects is that the uptake of new technology is often at a lower rate than purely technical issues would suggest is possible. Major changes in system architecture such as LFC, appear unlikely to be adopted in advance of changes which are evaluated as lower risk. To date and for some time in the future, it has been possible to provide large contributions to RPK/DOC improvements by increases in engine efficiency while maintaining fundamentally similar systems architecture for the aircraft as a whole. However, FBW and composite materials are two significant examples where both risk was reduced by demonstration in military service and obvious efficiency and effectiveness improvements

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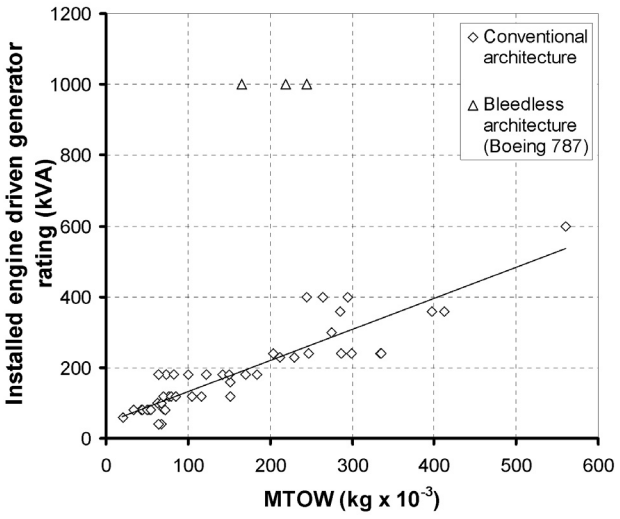


Figure 5. Installed electrical generation capacity of civil transport aircraft against maximum take-off weight.

could be identified. They were therefore adopted for civil transport aircraft and have been successful in their implementation.

The retarding effects identified, together with the historical examples given, suggest that the availability of a production ready new technology is a pre-requisite for its implication, but far from a guarantee.

4.0 ISSUES ASSOCIATED WITH FC IMPLEMENTATION

4.1 Certification (legal) issues

4.1.1 Safety

This section considers the certification issues associated with the implementation of an FC separation control system for high lift applications. The high level requirements for such a system would include:

- meeting specified aerodynamic performance requirements
- operating to a degree of efficiency at which tangible benefit is provided to the operator
- operating to a degree of reliability and safety sufficient to satisfy the requirements both of the regulatory authorities and operators

Electrical power generation is provided by engine driven generators with backup in the event of failure from the auxiliary power unit (APU), batteries and/or hydraulically driven generators powered by a ram air turbine (RAT). The power input requirements of the high lift FC system under consideration will therefore be subject to the same level of redundancy requirement as for other flight-critical electrical systems, which may include the flight control system and (in the case of the Boeing 787, for example) the environmental control system. The need to include capacity for flow control system operation in the event of major failure will influence the sizing of the backup systems in order to provide this redundancy.

The power required to operate the flow control system is likely to be significant. Calculations by Gomes for a SJA-based system for high-lift separation control applications on a single-aisle civil transport aircraft suggest a specific system mass based on electrical power required of approximately 1kg/kW[22]. This excludes any requirements for system redundancy, which will increase the specific mass value. Such considerations are critical to the future of FC in aircraft design, as the technology must compete against established (and generally less complex) geometric techniques for providing the required aerodynamic performance. For augmentation of the single aisle aircraft high lift system as discussed above, the required electrical power was calculated to be 93kW, of which the contribution of the flap system was of the order of 11kW. A similar study carried out by Crowther[33] applying steady blowing to a trailing edge flap calculated a flow power requirement of the order of 7kW at the orifice exit plane for the same flap application.

It is interesting to compare these power requirements with the available generation capacity of civil transport aircraft. Figure 5 illustrates the installed engine driven generation capacity of some civil transport aircraft, plotted against maximum take-off weight. The capacity of the APU has been excluded, as this is in general used only as a back-up facility in flight, particularly on ETOPS-certificated aircraft. Some spread in the data would be expected, due to the retention of common systems across versions of the same basic aircraft type, with differing certified MTOW values.

It is notable that the installed generation capacity of the bleedless architecture aircraft (this includes only the Boeing 787 variants at the present time) is approximately 2·5 to 5 times that of the conventional bleed configurations. One major advantage of this type of architecture is that, if more services use a single source of power, it is more likely that spare capacity can be used effectively. For example, a flow control system may be designed for high lift augmentation in the take-off and landing phases of the mission. During this time, galley services are unlikely to be in use. If both systems share an electrical supply, then the total system impact is likely to be less, than if the FC system required a separate dedicated compressed air supply.

In the next section, attention will be given to operational issues associated with FC implementation. The proposed use of flow control systems to augment the primary and secondary control surfaces of an aircraft, means that any failures of the system must be able to be accommodated by the flight control system and remain within the capabilities of the crew. Two significant areas of concern from an airworthiness perspective are the effect of FC failure during use, and the indications provided to the crew on system readiness before take-off.

It is a requirement for flight control systems that any powered elements should fail progressively, giving the pilot ample time to react. As FC is envisaged as an augmentation device for both the primary and secondary control surfaces, the demonstration of an adequate failure rate and provision of appropriate redundancy will be vital. For example, the complete failure of the trailing edge flap FC system on one wing would be analogous to asymmetric flap deployment. With current passive systems, this mode is avoided through monitoring of the flap position during deployment. The FC system would similarly need to ensure that symmetric performance was maintained.

A key benefit of FC is the ability to improve high-lift system performance such that either the number or size of the elements can be reduced. However, the ability to design for the actuated case will depend on the ability to prevent the failed operational case, which would inevitably lead to conservatism in the design. The failure rate and level of redundancy required will therefore be critical for both certification and in developing the business case for FC on commercial aircraft.

Civil transport aircraft must be equipped with a configuration warning system, which indicates by an aural tone when the aircraft is incorrectly configured for take off. This requirement has developed following several fatal accidents in which the aircraft involved had

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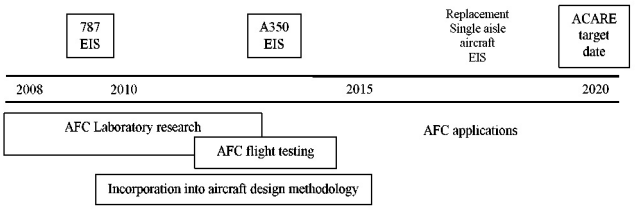


Figure 6. Timeline for development of active flow control technology. Relevant external events are shown above the timeband, with the proposed route to FC implementation below.

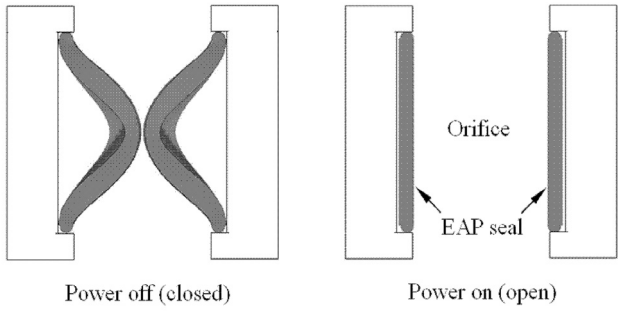


Figure 7. Schematic of an example EAP orifice closure concept for an SJA. The orifice is viewed in cross-section.

inappropriately configured high lift systems[34]. In an aircraft of the current technology level, these systems are based purely on position sensors detecting the configuration of the passive high-lift system components. However, if such passive systems are augmented or replaced by active systems, then such simple measures will become invalid. It would become necessary for the aircraft's systems to be able to test that the FC devices are working correctly.

For SJA systems, it may be possible to monitor the in-cavity pressures against a calibrated requirement. In this way, the aerodynamic performance of the devices could be inferred and any blockage be detected. It would be necessary to define a threshold number of functioning devices, which would mean potentially monitoring the function of a large number of systems. This could be carried out relatively simply by incorporating a microphone or pressure sensor into the SJA cavity wall. Another related method would be sensing of the current draw of the SJA units. At a given voltage, this would be altered due to changes in the cavity pressure.

A second possibility is the accurate monitoring of the boundary layer profile in the region over which flow control is to be exerted. Geoghegan[35] has presented a method for the off-surface measurement of boundary layer profiles using ultrasonic tomography provided by embedded surface sensors. This has the advantage over a calibrated cavity pressure measurement, in that the results represent an indication of actual rather than inferred performance, giving a higher level of confidence in the system operation. However, such a system would only be effective when a boundary layer had formed, i.e. when the aircraft was in motion. At the runway holding point before takeoff, a system based purely on this technique would not be able to function, however it would be possible to provide warning at a similar time to that at which engine power settings are confirmed during the take-off roll. Perhaps an effective use of boundary layer tomography would be the monitoring of changes in boundary layer shape over a number of flights, in order to highlight change in the effectiveness of the FC system and trigger maintenance long in advance of failure

Protection from environmental damage was a significant issue identified in LFC research, and will be investigated for FC systems in the next section. In LFC systems, the principal problem is not one of clogging of orifices by debris, but of overall surface cleanliness. FC systems are not concerned with the maintenance of laminar flow and will be less affected by this problem. However, electro-mechanical transducers lack both a natural high pressure source for orifice cleaning, as can be provided by pneumatic LFC or FC systems[31]31, and a natural source of heating for deicing. In many cases, proposed LFC systems have been designed to incorporate the leading edge deicing system, both in order to reduce complexity and because effective deicing is critical to the provision of laminar flow. Therefore, despite the work completed to date to create practical LFC systems, there are many further issues to solve with FC systems, particularly in the case of electro-mechanical devices.

The proposed FC systems would be operated at low altitudes and when the aircraft is on the ground. The flow control devices must therefore be resistant to the effects of contaminants including ice, water and insects. Proposed LFC systems have typically used perforated skins with arrays of small holes. These generally have a diameter of the order of 0·1mm, with the skins forming part of the aircraft structure. The orifice diameters of FC systems proposed for high lift applications are generally an order of magnitude larger, in the range 1-3mm. This is of a similar size to the orifices in a pitot-static system. The relatively large orifices therefore have a significant possibility of allowing contaminants to enter the systems, when compared to LFC systems. Additionally, once contaminants have entered removal may provide a significant problem due to the lack of a high pressure blowing source. Pitot-static systems are equipped with heating elements and drain holes to address the contamination, but significantly differ in requirement to FC systems in that they must remain operational at all times. They are also typically external to the structure which simplifies the geometric requirements of this provision. EMFAs in particular are integrated electrical systems operating in niche areas, it seems more likely that they will be assembled as modules and fitted into bays in the aircraft structure, which would not be conducive to drainage.

One possible approach to environmental protection of EMFA systems is to provide an orifice that can be closed during the majority of the flight, when the device is not in use. The provision of such a capability is a significant challenge; the requirements for such a cover would include:

- the capability of cost-effective fabrication on the same scale as the SJA system
- operation by electric actuation
- acceptable mass penalty
- acceptable aerodynamic penalty for orifice flow
- the capability of operation throughout the range of atmospheric condition encountered by civil aircraft

The use of electro-active polymer (EAP) based orifice closure devices offers one possibility to meet the above requirements. EAP actuators are typically silicone elastomer sheets incorporating compliant electrodes. Activation of the electrodes causes a compressive force to be placed on the sheet, which due its incompressibility is forced to displace out of plane. It can be seen that compression is achieved normal to the ply plane and expansion parallel to this plane, which could enable the device to expand or contract in either the power on or off cases, depending on arrangement. Larger contractions can be achieved by a folded arrangement of a pair of electrodes, a so-called stack actuator.

To date, much of the literature has focused on the use of EAP technology in the development of artificial muscles for robotics, although some work has been completed on EAP active dimple flow control actuators[19]. Compared with other active materials such as shape memory alloys, EAP offers large displacement (strains greater than 10%), low power consumption and low density[34]. The large

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achievable strains are of particular importance in this context, as the space available around the orifice is limited. A particular requirement for the application discussed here is for continued operation over a large temperature band, typically in the range between –60°C and 60°C. Silicone-based materials can readily be tailored to this requirement. Manufacture of EAP actuators can use micro manufacturing techniques, including printing and spin-coating. The latter in particular provides a method of achieving consistent homogenous silicone layers. Recently, compliant electrodes using carbon grease have been developed, providing a cost effective solution to this challenge.

Figure 7 illustrates a promising concept for an EAP configuration. A stacked actuator is used; with power off the device is closed and makes use of buckling to further increase the deflection achieved. With power on, the device compresses and moves into the orifice recesses. This configuration could be implemented in two-dimensional slot orifice or a three-dimensional circular/elliptical orifice.

This work has made reference to the likelihood of environmental legislation influencing aircraft design. In the next section, some potential issues in this field are identified.

Noise is a key issue which impacts on both certification and the commercial prospects of a civil transport aircraft. New aircraft must meet current noise standards and those which are envisaged to be in place in the life cycle of the fleet. The requirement to meet noise standards for operation from particular airports may even cause compromises to be made with cruise fuel burn. The Airbus A380 for example is expected to carry a cruise fuel burn penalty of the order of 1%, due to the increased engine fan diameter required to reduce noise in night operations from certain airports[37].

In the high lift configuration and particularly with the undercarriage deployed, significant noise sources are introduced. Some of these have been found to be attributable to the interacting vortices and wakes caused by the flap ends and slots[5]. Given the current research, it is reasonable to presume that FC could be used to eliminate some of these problems by improving simply hinged flap performance and the control of unsteadiness in separating flows. However, the flow control devices tested often introduce additional noise sources during their operation. SJA devices, by their nature, depend on acoustic amplification at resonance to achieve high exit velocities, and hence emit considerable acoustic energy at the frequency of operation. Individual type SJAs tested in laboratory conditions have tended to operate at frequencies of $1\text{kHz} \leq f \leq 3\text{kHz}$[23]. Slot type devices have tended to operate at frequencies below $f = 1\text{kHz}$[16], with a similar range identified for central source pulsed pneumatic systems[38]. What this means in effect is that all flow control demonstrations to date using these devices have been firmly in the audible range. Aircraft noise is of course a target for improvement, not least in respect of the ACARE targets discussed above, and it seems unlikely that devices that generate significant tonal noise will find favour.

In order to avoid these problems, it is possible that FC devices generating tonal noise may have to operate in the ultrasonic range. From the point of view of the EMFA actuators considered, there seems to be no fundamental reason why this concept should present any insurmountable problems.

A further noise issue that may require attention is the tonal frequencies generated by the shape of the orifice. Boeing has modified the shape of some leading edge deicing exhaust ports from circular to rectangular for noise reduction purposes[39]. Orifice closure as suggested in the previous section could mitigate this problem.

4.2 Commercial issues

To be commercially competitive, the dispatch reliability of civil transport aircraft must be very high, with a specification value typically greater than 99%. The ability to meet the required dispatch reliability target is therefore a critical factor in system design and will govern many of the choices madexl. The aircraft may for example be designed with additional redundancy in its systems above that required for certification on safety grounds, in order to meet this commercial requirement.

The efficiency gains proposed from flow control may be realised through a reduction in the size or relaxation of geometry requirements of the high lift system. A severe degradation of performance with flow control inoperative could therefore result. On the other hand, the benefits are unlikely to be realised if the high lift system is sized to operate routinely or with high effectiveness without flow control. This implies that the FC system will need to be sufficiently operable (functional due to inherent redundancy), in order to form part of the minimum equipment list for dispatch. It is interesting to note however that in one study concerning LFC, an operator involved suggested that this system should not be required to be operable for dispatch[11]. Obviously this would be at the cost of reduced L/D performance achievable. It could be therefore that in order to meet the requirements of the operators, a compromise would have to be struck between the optimisation of the low speed FC augmented configuration and the performance achievable with FC off. For this to be an appropriate requirement, the increasingly marginal gains due to FC would need to be sufficient that the overall system performance was still improved, in order for FC to remain viable.

In addition to the functioning of the FC system itself, the associated sensor systems (including those which provide input to the take-off configuration warning system, Section 4.1) would be required to be operational for dispatch. In the case of direct-bleed systems, the architecture adopted would be similar to that currently used for wing anti-ice systems, and it is reasonable to use the certification requirements of that system as a model. The main requirement is the detection of leaks in the system, which may lead to reduced performance due to pressure loss and overheating of the wing structure. Typically two independent sensor systems are provided to allow dispatch with one inoperative[41]. In the case of EMFA based systems, the cavity pressure or boundary layer profile sensing systems would also be required to operate on two separate loops.

As illustrated in Section 1.1.1, the challenge for flow control is to provide either increased absolute performance or a reduction in the cost required to provide a given performance. The issue of difficultly in assessing the potential benefits and particularly the potential costs that may be caused by the incorporation of a currently immature technology was also highlighted.

The major sources of cost attributable to the high-lift systemxl have been summarised as:

- significant time to design and test
- complex flows, geometry and support systems
- weight
- high parts count
- maintenance in service

For a given ΔC_L, augmentation of high-lift systems by flow control has the potential to reduce all of these cost sources with the exception of the first, principally through reductions in element area and number It has been shown[10] by reference to current systems that the replacement of slotted flaps by simply hinged flaps can significantly reduce the first cost of the high-lift system. However, the FC system itself presents both a first and recurring maintenance cost.

The commercially acceptable balance between first and recurring cost is based on the effect of cost change to give component life extension, when compared with the cost of replacement parts and time out of service.

4.3 Timeline for single aisle replacement aircraft

As has been stated in Section 3.2 a time span of 10-15 years can be expected to elapse before a significant new technology may be implemented in production. The implication of the ACARE target

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date is that the prototype new technologies will be undergoing full scale flight test in the near term, in order to provide sufficient data for future aircraft designs. The laboratory scale equipment which is the current state of the art of many potentially useful technologies must be improved to reach the required standards of effectiveness (ability to provide the required physical authority), efficiency (ability to provide the required effectiveness at viable cost) and reliability if they are to contribute. For example, a target has been set by the EU AVERT project for the flight testing of FC technology from 2012, specifically in order to meet the 2020 target for widespread implementation. The timeline for technology development from the present day to the ACARE target date of 2020 is illustrated in Fig. 6.

The next generation of single aisle aircraft is expected to be developed for entry into service (EIS) sometime after 2017[43,44]. In unit terms, this represents by far the largest sector in the 100+ seat transport aircraft market, and therefore a major target for any new technology. Such aircraft spend a proportionally greater part of each flight in the low speed regime, due to the short sectors on which they are typically employed. This makes the low speed aerodynamics of the aircraft and the use of separation control methods highly relevant. This short-medium range, single aisle cabin aircraft market is dominated by the Airbus A320 and Boeing 737 families. The former entered service in 1989 and the current generation of the latter in 1997, although it is based on a design that originally entered service in 1968 and undoubtedly retains some features inherent in that technology level. The implication is that (certainly in the case of the A320) the earliest examples of these aircraft types are due for replacement, although the only current replacement options are newer examples of the same types.

A key enabler for implementation is the availability of sufficient design data to populate conceptual modelling databases. This will be a required output of both laboratory and flight test work. It is possible that for risk reduction purposes secondary applications such as augmentation of control surfaces may initially be chosen, as described above for composite materials. However, it is less clear that the airline customers would benefit from such a change, as the efficiency gains achieved would be small. It may be noted that composite materials were able to demonstrate advantage to the end user in secondary applications, through reduced mass and part count.

Another possibility for risk reduction would be the use on a small test fleet of in-service aircraft, for which a precedent[12] was established by riblet technologies. Here, the aim would not be large gains in efficiency but the proof of concept from the perspective of system design and maintenance. Application to high risk but high payoff areas such as complete high lift systems could then follow with the benefit of in service experience.

5.0 CONCLUSIONS

This aim of this paper is to introduce some of the challenges which must be overcome before active flow control can be introduced on civil transport aircraft. Some conclusions that can be drawn are:

- At the current rate of progress, it does not appear likely that flow control will be ready to contribute to the next generation of single aisle aircraft, which are projected for service from 2015 onwards
- The introduction of new technologies into civil transport aircraft design often occurs over a period of many years, with the potential business impact of system immaturity being addressed by long-term demonstration.
- There are some parallels between flow control for separation control and the development of laminar flow control (LFC) technology, but despite many years of research and successful flight demonstrations of effectiveness, LFC has still to find a production application.
- The expected improvement attributable to separation control is much less significant and remains largely unproven.
- The best efficiency improvements with flow control are likely to be achieved when synergy in systems design is considered, which implies that the more electric aircraft of the future uses electrically powered flow control systems
- Electro-mechanical fluidic actuators appear to be the flow control technology most consistent with future predominantly electric systems architectures .
- The impact of certification requirements on the use of flow control must be understood to allow its implementation; parallels exist between this new technology and previous major changes including digital fly-by-wire flight control systems and the introduction of ETOPS operations. Some of these issues are:
- Dispatch reliability with flow control must be at least as good as that achieved with mechanical high lift systems, which will control the required level of redundancy to meet regulatory and commercial requirements
- The size of the orifices for electro-mechanical transducers and the lack of a source of compressed air for cleaning, implies that some kind of orifice closure mechanism is required. EAP has been suggested here as a viable technology
- Due to the need for further reductions in aircraft noise, EMFA systems are likely to be required to operate in the ultrasonic range
- At the current rate of progress, FC is unlikely to contribute to improving the efficiency of the air transport system by 2020.
- The next generation of medium and long haul aircraft are either in production or in the final stages of development at the present time. These aircraft types are unlikely to be replaced in the next 20 years.
- The design data required to achieve sufficient confidence in FC technology is unlikely to be available in time to contribute to the next generation of single-aisle aircraft. To address this situation, more rapid system development leading to simulated airline operation, as conducted with LFC is required.

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