INTEGRATED EQUIPMENT SYSTEMS FOR A MORE ELECTRIC AIRCRAFT – HYDRAULICS AND PNEUMATICS

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Abstract

This paper traces a brief outline of current work towards the More Electric Aircraft. It then summarises the intentions of the European Commission part-funded POA 'Power Optimised Aircraft' project in the direction of the More Electric Aircraft, and outlines current conclusions on more-electric high-lift, landing gear and environmental control systems.

1 Civil transport and systems architectures

The state-of-the-art in aircraft systems architectures consists of complex (but well understood and firmly established) technologies which make up the equipment used to power and fly a modern civil aircraft. Here, an Equipment System fulfils a major functional aspect of an aircraft and an Architecture is defined as the overall way in which Systems are assembled within the Aircraft.

In a conventional architecture (a basic schematic is shown in Fig 1), fuel is converted into power by the engines. Most of this power is expended as propulsive power (thrust) to propel the aircraft. The remainder is transmitted via, and converted into, four main forms of non-propulsive power.

- Air is bled from the engine high-pressure compressor(s). This pneumatic power is conventionally used to power the Environmental Control System (ECS) and supply hot air for Wing Ice Protection System (WIPS).

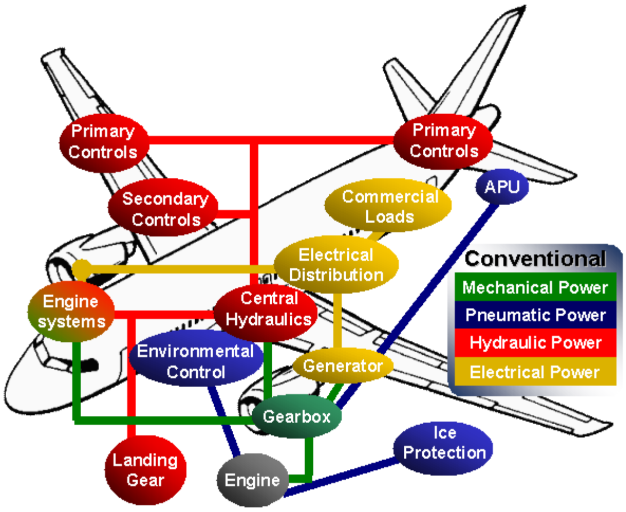

Fig 1: Schematic of conventional power distribution

- A mechanical accessories gearbox transfers mechanical power from the engines to central hydraulic pumps, to local pumps for engine equipment and other mechanically driven subsystems, and to the main electrical generator.
- The central hydraulic pump transfers hydraulic power to the actuation systems for primary and secondary flight control, to landing gear for deployment, retraction and braking, to engine actuation, to thrust reversal systems and to numerous ancillary systems.
- The main generator provides electrical power to the avionics, to cabin and aircraft lighting, to the galleys, and to other commercial loads (entertainment systems, for example).

This conventional distribution of energy is fully reflected in the way aircraft systems are classified and procured today.

2 The Systems approach

Conventional equipment systems on civil aircraft are a product of decades of development by the systems suppliers. Each system has become more complex, and designers have striven to overcome the myriad of interactions between equipment by increasing the efficiency of each system. Despite this, many of the large energy users on board remain inefficient, largely due to a historical avoidance in trying to solve this problem at the level of the whole aircraft.

To address this issue, hybrid or bleedless air conditioning systems, the "More Electric Engine" (MEE), fuel cells, variable frequency generators and distributed system architectures are just a few of the technologies vying for space on the next aircraft. Some are already being put onto the Airbus A380 and the Boeing B7E7, the first and second civil applications of the much talked about "More Electrical Aircraft" (MEA). The advantages of More Electrical Systems (such as higher efficiency, potentially improved maintainability and higher reliability) are not constrained to aircraft, and other transport systems, such as marine propulsion, are moving towards their application [1].

The road to the civil transport MEA is a historically long one, and it consists of a number of systems level developments which are now maturing in the direction of integrated aircraft. The major projects in the systems field were supported by European Commission, French DGAC, UK Department of Trade and Industry (DTI), US Air Force Research Laboratories (USAFRL) and US Defence Agency (DARPA) funding ([2] has more details).

3 The Aircraft approach

Despite the trends at equipment system level, there are fundamental concerns with this "Power-by-Wire" (PBW) systems development approach [2]. The collection of PBW systems to create an MEA is no longer sufficient. The effects of the new systems in terms of safety, cost, reliability, maintenance, power management and fuel usage at the total aircraft level all have to be juggled against the technical benefits of implementing these systems. These issues have to be treated as simultaneous goals, and the aircraft has to be optimised to achieve them all.

In the late 1990's, two research programmes began to look at MEA from an aircraft level perspective.

The TIMES - Totally Integrated More Electric Systems - project [3] began in April 2001, and is sponsored by the DTI under the 'CARAD' programme. TIMES uses previously developed systems, and integrates them in an electrical network to determine the viability of using such a network in a future MEA. The focus is on establishing the trends for an MEA network, based on the current development status of MEA enabling technologies. Fan shaft driven embedded generation [4] is one example of these.

The US Air Force Research Laboratory MEA contribution to the 'More Electric Initiative' [5] resulted in the implementation of validated MEA enablers, such as high density power generation, into actual aircraft. This initiative is still running, but has already resulted in the installation of more electrical systems on the Joint Strike Fighter and the Boeing 7E7.

4 POA – the next step

Power Optimised Aircraft (POA, [6]), which began in January 2002 and will run for 4 years, is the most recent and most integrated research project to address the creation of a more efficient aircraft. As it is widely believed that electrical equipment systems are more efficient that conventional ones, most of POA is based on a vision of an MEA for the future. At the *aircraft* level, the project should demonstrate a 25% reduction in peak non-propulsive power usage, a 5% reduction in fuel consumption, a reduction in equipment weight, and no overall degradation in production costs, maintenance costs or reliability.

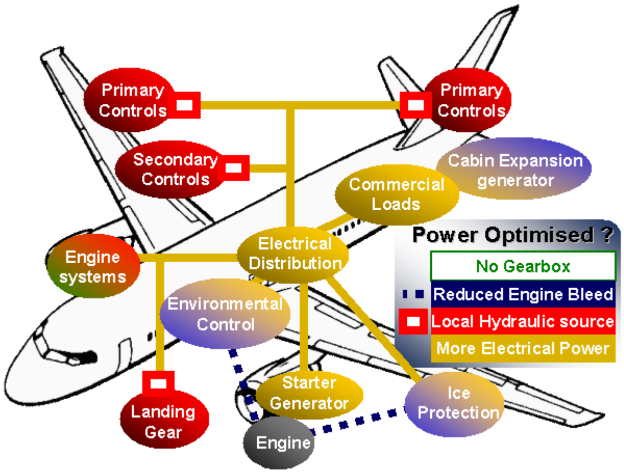

Fig 2: A potential optimised architecture

This will be achieved not only through improving individual systems, but also by completely altering the way in which the architecture of aircraft systems is designed (Fig 2). The project is focused on validating the systems that could lead to a 350 passenger twin-engine power optimised aircraft.

4.1 Systems aspects of POA

In the area of **Engine Electrical Systems**, embedded starter/generation, variable speed generation, DC power generation, high voltage DC bus systems, electrical fuel, oil and engine actuation systems, and magnetic bearings are being addressed.

In the area of **Aircraft Electrical Systems**, novel distribution architectures, network interactions, protection, high voltage DC commutation, wiring and load management are being examined.

In the area of **Actuation Systems**, alternative architectures with electro-hydrostatic, hybrid and electromechanical actuation for primary and secondary flight control, as well as new landing gear, braking, nacelle actuation and horizontal stabiliser architectures are being examined.

In the area of **Pneumatic Systems**, more electrical environmental control systems (ECS) and wing ice protection systems, as well as the use of vapour cycle cooling, cabin energy recovery and fuel cells in aircraft are being considered.

5 How MEA affects equipment systems

The electrification of the aircraft makes most sense when it is done through the electrification of energy types. This primarily has consequences on the conventional 'loading' systems. However, the electrification of these, in turn, has huge consequences on the electrical power generation system (EPGS). In this paper, we will not deal with all aircraft systems which are affected by MEA, but summarise the consequences of MEA for the design of some hydraulic (secondary flight controls, landing gear) and pneumatic (environmental control) systems.

5.1 High Lift Systems

High Lift Systems (HLS) in aircraft are used to change wing configuration to provide increased take-off and landing performance.

In principle, an aircraft could take-off and land without such a system. However, the runway length necessary to accelerate or decelerate would be unacceptable, whilst the aircraft on-ground speed required would be beyond the limits of safe operation.

The nature of their function means that the HLS is a high power-consumer for a very short time in a flight cycle.

5.1.1 HLS Architectures

The vast majority of HLS in commercial transport aircraft consist of one or multiple power control units (PCU), a mechanical power distribution and conversion system and devices to provide system irreversibility in the case of system failures (see Fig 3 for a schematic).

5.1.2 State of the Art Power Supplies

Today's aircraft use electric and/or hydraulic power to operate their HLS. As a very rough classification, there are four system categories:

- Electric motors and brakes in HLS with power consumption of less than 2 to 3 kW
- Hydraulic motors and brakes in HLS in mid-size and big commercial transport aircraft, e.g. all Airbus from A318 to A340-600.

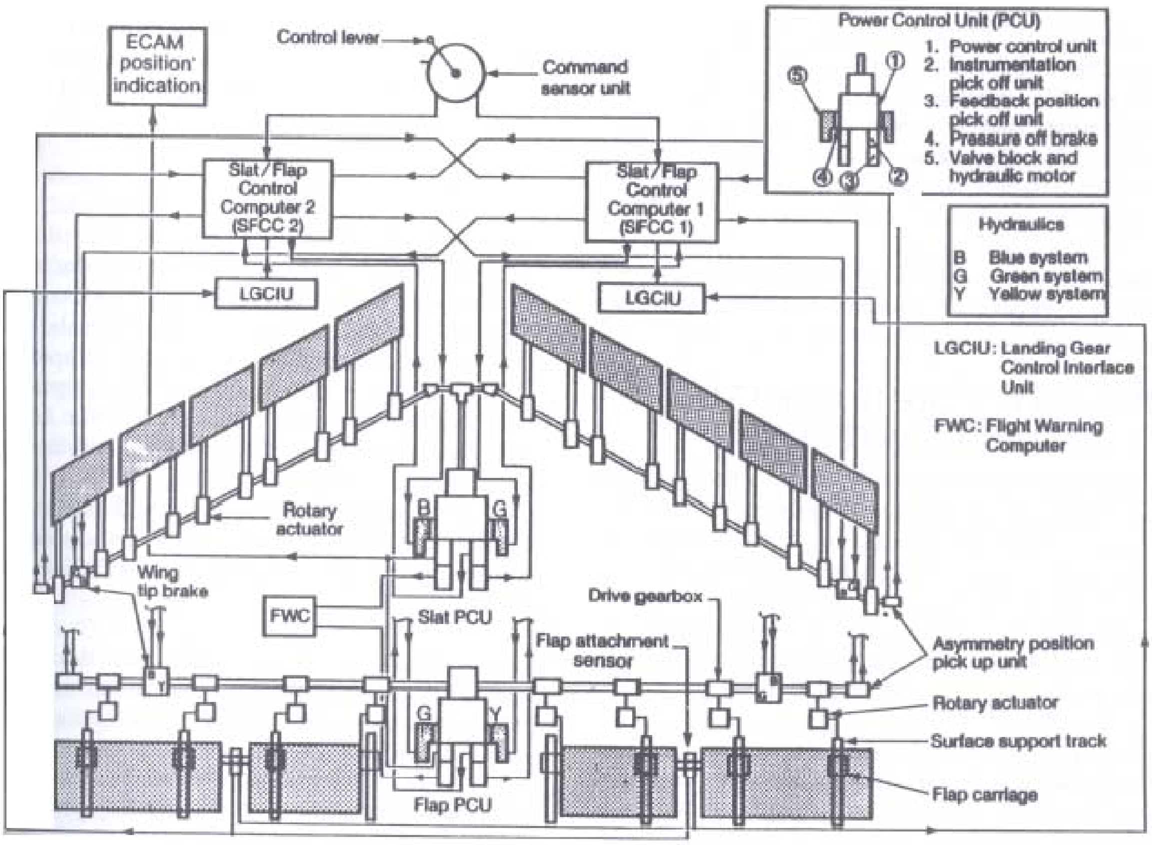

Fig 3: Schematic of Airbus A320 High-Lift System (Airbus)

- Primary hydraulic motors and electric back-up motors e.g. in Boeing Commercial Airplanes.
- "Hybrid" (i.e. hydraulic and electric) drive units combined with electric brakes e.g. Airbus A380.

5.1.3 Choice of HLS architecture

Each of the above mentioned HLS architectures with power consumption >3 kW is driven by the aircraft level power supply architecture:

- Airbus aircraft have two major and one auxiliary hydraulic power circuits (called Green, Yellow and Blue). The HLS are connected to all three systems. A high level of availability of the HLS is thus ensured.
- Boeing aircraft also have three hydraulic circuits (called Central, Left and Right), but the Central System is the most essential, therefore the Boeing engineers call it the "Golden". HLS primary drives are connected to the "Golden". In this architecture, the loss of the Central hydraulic system is compensated for by the back-up motors.
- The A380 has only two hydraulic circuits. Therefore, to provide sufficient HLS availability, one additional electric drive is used.

5.1.4 HLS in the More Electric Aircraft

The simplest approach to integrate a HLS in a more electric aircraft is to exchange the hydraulic drives and brakes for electric units. Unfortunately, there is still a disadvantage of electric motors and brakes with respect to their lower power density and the weight of the high power distribution system. Even the technology of brushless DC motors cannot currently compete with hydraulics, due to their need for complex and low-reliability motor control electronics.

A trade study conducted in POA revealed that a distributed HLS, including separate drives and brakes for the inboard and the outboard flap panels, provides an opportunity to reduce the peak power consumption of the aircraft by operation of the inboard and outboard flaps in a sequence. This architecture and operational mode would moderately increase system cost, weight and complexity. However, an aircraft level advantage in power management is expected.

Given their dependency on the aircraft level power supply architecture, HLS in their conventional functionality can contribute little to an MEA concept. Simple replacement of hydraulic drives with electric will make the HLS heavier, more costly and less reliable. The advantages of a more electric HLS are to be seen at the aircraft level.

5.2 Landing Gear System

This section confines itself to the *actuation* of the landing gear, i.e. subsystems relating to retraction and extension of the gear and doors, and to steering. These functions are the largest users of hydraulic energy in a state-of-the-art transport aircraft.

Thus, in spite of an extremely short operating time per flight cycle, the power requirement for landing gear actuation is a major factor of the capacity/performance of the three central hydraulic power circuits.

5.2.1 Decentralised versus centralised supply

A trade study in POA showed that decentralised hydraulic power supplies (removing the central hydraulic circuits and replacing them with local motor-driven hydraulic pumps, called a "motor-pump package") can fulfil the power density and efficiency requirements of the landing gear of a large transport aircraft. Compared to the conventional central hydraulic circuits, such decentralised power supplies need only to be switched on when local hydraulic power is required. For the entire aircraft, energy usage can be reduced significantly in this way. However, such "Power on Demand" supplies can offer new architectural possibilities for landing gear.

The two main characteristics considered in developing a new actuation concept with local hydraulic supplies in POA are energy efficiency (regarding the weight of the system) and reliability. A main assumption of the analysis is that the landing gear and actuators are not changed at all. At a first pass, a constant pressure hydraulic system with conventional 'restrictor control' could be employed. Though it requires less effort in development, the entire system is still dissipative in this case. Note that the energy dissipation in that short duration of landing gear system (LGS) operation would not be a substantial problem but it has a significant influence on the dimension of the hydraulic power supply itself. The higher the dissipation, the bigger and heavier the power supply will have to be.

If the LGS has its own motor-pump packages, it can control actuation by means of the flow rate of the pump (displacement control). Snubbing devices based on 'restrictor control' are no longer necessary. Consequently, no more electric energy on board will be converted into hydraulic energy just to be dissipated immediately after. Thus, regarding energy efficiency, 'displacement control' is a preferred choice.

5.2.2 Similarities with EHA

This type of actuation control without a servo valve, using a motor and pump, resembles the Electro-Hydrostatic Actuator (EHA) of state-of-the-art MEA flight control systems (FCS).

The major difference between the FCS EHA and LGS actuation for MEA presented in this paper is that the FCS EHAs are typically equipped with a single, balanced hydraulic cylinder whereas one local motor-pump package of the MEA LGS supplies several hydraulic subsystem cylinders, like door actuator(s), gear retract actuator and steering motor in the case of the nose landing gear. With the exception of the 'rack and pinion' type steering, these cylinders are usually unbalanced ones.

5.2.3 Simplification of the LGS in MEA

Because the actuation of each subsystem can be managed sequentially, it is possible to supply the subsystems by use of a single motor-pump package. Like an electric system with a rotary switch, the actuators will selectively be set to move. This concept is called 'Multi-Supplying Electro-Hydrostatic Actuation' (MS-EHA), illustrated in Fig 4. The following are some of its advantages:

- No separate, disassociated motor-pump packages are needed for each subsystem. This improves cost, maintenance and availability of the subsystems.
- Whenever the gear is in transit, regardless of the direction of gear movement, the extension ports of the door actuators will remain energised, so that the doors may keep the open position. During high aerodynamic loads/gusts or a bird strike, the doors will yield in order not to damage the hinge, then come back to the full open position as soon as the relief valve caulks the hydraulic line again (Spring Back).
- More than one actuator can be energised to move. Compared to FCS EHAs, the requirement on accuracy is not so high, so that two or more door actuators can be supplied simultaneously by a single pump.
- When the mechanical emergency free fall is activated, hydraulic fluid will be fed from the extending gear actuator into the door actuators, so that the doors will be actuated by the waste energy from the high pressure created by the falling gear. The doors automatically re-open at a disturbance during emergency actuation in the same manner as in normal operation.

The prototype hardware of this unique design concept has been successfully constructed and is being evaluated.

This simplification of the hydraulic circuit is achieved by means of multi-functional valves (MFV) which allow minimising of control effort with maximised reliability of the total LGS. The designs of the solenoid activating MFVs are chosen in such a way that a single integrated spool replaces numerous valves and hydraulic components the conventional LGS have been equipped with (this can be seen in Fig 4). This arrangement keeps the number of the simultaneous valve operations, and consequently the necessary solenoids, to a minimum. There is no sequencing which needs to energise more than one solenoid. High reliability is achieved in this way.

Despite the high integration valve spools, the manufacturing and maintenance costs of the LGS will be reduced since the shape of a spool and consequently its reliability shall be maintained throughout its whole life.

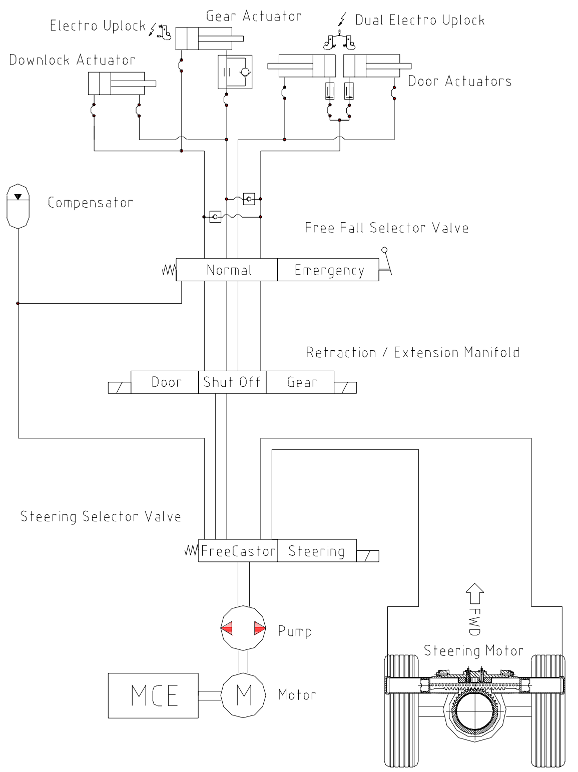

Fig 4: Simplified landing gear architecture for MEA

5.2.4 Consequences on the FCS

Naturally, de-centralising LGS supply cannot be done without ensuring that the FCS, particularly the primary FCS, still meets its safety requirements. Thus, this architecture of LGS is most feasible in an MEA with electrical flight control, or an FCS supplied by the same local motor-pump packages as the LGS. This type of integration consideration is dealt with in POA.

5.3 Environmental Control System

The task of an Environmental Control System (ECS) is to control air temperature, to pressurise relevant aircraft compartments, to provide sufficient ventilation and fresh air to passengers, to control the level of humidity within acceptable limits in the cabin, and to remove pollutants. The core system where air is conditioned are the so-called “packs”.

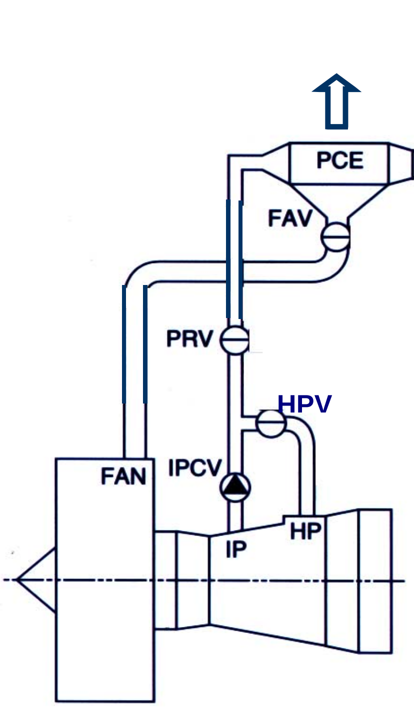

Fig 5: Typical engine bleed air system

5.3.1 Conventional ECS

Currently the ECS Packs of large civil Aircraft use air which is bled from the engine compressor to provide conditioned air (flow, pressure, temperature) to the cabin (Fig 5). As the thrust produced by the engines depends on aircraft flight phase, the pressure of the engine bleed air varies such that it is necessary to use two different ports: the Low Pressure (LP) or Intermediate Pressure (IP) port which is used during most of the flight, and the High Pressure port (HP) which is used when the engine is operating at low thrust (especially in landing, hold and descent conditions). The choice of the bleed port (LP/IP or HP, controlled by valves LPCV/IPCV and HPV) for the supply of the ECS (but also the Wing Ice Protection System - WIPS) is driven by the available air pressure and is controlled by complex laws.

The pressure of the air delivered is limited by the Pressure Regulating Valve (PRV) and its temperature by the Pre-Cooler (PCE) which uses engine fan air to cool down the air coming from the core of the engine. The Fan Air Valve (FAV) modulates the coolant flow so that the temperature of the air leaving the PCE doesn’t exceed 200°C.

Bleeding air from the engine has an impact on engine fuel consumption. This depends mainly on the following parameters: air mass flow, air pressure, engine thrust.

It is also obvious that the ECS has to cope with all energy level supply situations coming from the engine, regardless if the air has a low or high temperature and a low or high pressure: the tasks to be fulfilled remain the same.

This means that the ECS has to be designed for the worst case (low pressure and high temperature), but that when flying conditions are not so stringent (most of the time), the ECS supply system is oversized, and the ECS is supplied by high levels of energy that it doesn’t need (this occurs particularly during the take-off and climb phases): the engine provides air with a high pressure which is reduced (wasted) by the PRV and Flow Control Valve (FCV) at the inlet of the Packs.

5.3.2 Electrification of the ECS

At aircraft level, the electrification of the ECS is a key enabler of the MEA as it is the biggest steady state power consumer during aircraft cruise, but could also allow to save a lot of fuel, due to its consequential adaptability and lower impact on the operation of the engine.

Fig 6 shows the approximate power consumption to realise the pressurisation and ventilation as well as the cooling of an aircraft for 100 and 350 passengers (valid for a cruise flight at 40,000 ft, hot day conditions).

The values of electrical power consumption of a full electric ECS are directly linked to the number of passengers, as the number of passengers determines the fresh air flow to be introduced into the cabin.

Although the values reported in Fig 6 are approximate, they give an order of magnitude of the needed electrical power to be supplied. For an aircraft with 350 passengers the electrical power needs will be in the range of 400 kW and will therefore largely influence the sizing of the Electrical Power Generation System (EPGS).

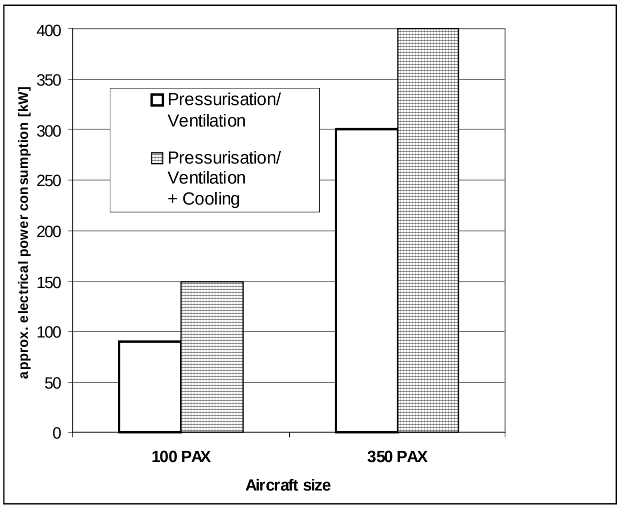

Fig 6: Approximate electrical power consumption of a full electric ECS depending on the aircraft size.

5.3.3 Benefits of electrification of the ECS

The benefits of the electrification of the ECS are numerous and some of them are listed below:

- No direct-intervention of the ECS in the operational cycles of the Engine. An electrical ECS will allow the engine compressor to be designed independently from the needs of the pneumatic systems.
- A higher efficiency engine can be realised with a higher bypass ratio (fan flow divided by core flow). This is because the mass flow of air required by the ECS is taken from the engine core flow. The more this core flow is reduced, the higher the impact on fuel consumption the ECS bleed becomes. The potential for reduction in core flow may even become limited due to the need to provide the aircraft cabin (and hence the ECS) with a minimum amount.
- Unlike a conventional ECS, where the energy source is the engine compressor, and therefore the power level depends on the flight phase (high power level during the climb and low level during descent), the electrical ECS will demand only the power needed to perform its tasks and not waste energy by dissipating high pressure air.
- During some flight phases the minimum thrust produced by the engine can be driven by the ECS, which requires a minimum pressure to fulfil its tasks. This leads to an additional aircraft fuel consumption and prevents the aircraft from flying a fuel-efficient mission profile. An electrical ECS would allow the segregation of engine thrust from ECS airflow needs.

5.3.4 Challenges to electrification of the ECS

Of course the electrical ECS has not only advantages, and some challenges to make it viable are evident:

- Due to the high electrical power consumed by the ECS, the size of the generators has to be appropriate. The challenge is much higher for twin engine aircraft and especially for the failure case one engine off, where half of the generators have to deliver more than half of the ECS power consumption for normal operation.
- The deletion of engine bleed air extraction for the ECS will deliver its full positive potential only if the other aircraft system using a large amount of engine bleed air, the Wing Ice Protection System (WIPS), uses another power source. The pneumatic power of the WIPS has to be replaced by electrical power, and the current power consumption of this system is tremendous when icing conditions are encountered. Alternative solutions, including electro-thermal, electro-impulse and electro-mechanical de-icing are being examined in POA.
- So as to built a compact, efficient and low weight ECS, it is necessary to develop turbo-machinery working at high speed. These motorised air cycle machines (MACM) have to work in the speed range of 50,000 rpm. For the cooling of their motors, a lot heat has to be dissipated over a small surface. Air cooled motors are feasible for the high power MACM needed to realise a full electrical ECS for a 350 passenger aircraft, but the challenge is not easy to overcome.
- The realisation of the electrical ECS will probably simplify the engine (deletion of bleed port, of bleed valves and of the pre-cooler) and its control, but will make the ECS more complex, as it will have to produce pressurised air by itself. This higher complexity will result in more weight,

installation space and costs. These have to be balanced against the benefits to the aircraft.

5.4 Conclusions at System Level

For each major system, a number of possible architectures have been defined in POA, each of which is feasible in terms of technology and function. Some of the work done for high-lift, landing gear and ECS has already been described in this paper. Similar studies for all main systems show that at this level, there are both advantages and disadvantages to MEA systems. The results so far show that generally,

- More Electrical systems **tend to be heavier** than their conventional equivalents. This is valid for most large systems, and the weight increase is based on conservative estimates relating mainly to heavy power electronics and heavy drives, both of which are absent in a conventional aircraft. This is the price to be paid for transferring hundreds of kW of electrical energy through the aircraft.
- More Electrical systems **tend to be more energy efficient**. As we have seen from the previous examples, this does not necessarily mean that all of these systems are more efficient at the component level. Although in most cases the electrical alternative produces fewer losses, the largest amount of energy saving can be seen in the lack of losses between the energy source and the end user.

  This can be seen in that an aircraft that no longer needs to waste bleed pressure and temperature, no longer requires restrictors in the hydraulic systems, and no longer requires engine systems to be dependent on engine speed or thrust is bound to be energy saving. This saving can be translated into reduced fuel burn.
- More Electrical systems **tend to have higher reliability**. The replacement of a bleed based ECS by an electrical ECS, for instance, has shown benefits in reliability. The example of landing gear shows that additional simplification of MEA systems can be achieved which leads to higher reliability. This all eventually translates into lower airline maintenance costs.

6 How equipment systems affect MEA

The only comprehensive assessment of how equipment systems should be designed can be obtained when these systems are put together as an aircraft. In POA, there are many possible aircraft combinations, ranging from minor changes in the state-of-the-art to the "all electrical aircraft" that may exist in the near future.

In POA, the full results will not be known until the end of the project, but the trends show some important aspects of MEA, many of which imply a change in philosophy of the way we consider aircraft systems:

- **Decreasing engine autonomy**. The engine is no longer the independent power plant that it is often considered to be. It has to be fully integrated with the aircraft electrical concept. Consider that a conventional engine can still function autonomously if the aircraft systems fail, but a More Electrical Engine is dependent on the aircraft electrical system (and vice-versa) for its power.
- **Increasing availability**. The use of four generation sources of electrical power (two in each engine) increases the availability of power to each system with respect to the conventional aircraft. This implies that an MEA may have a higher availability of power than a conventional aircraft, potentially leading to an easier attainment of system safety requirements.
- **Importance of snowball effects**. The power off-takes at the engine from all the aircraft systems are responsible for 3-5% of the total power produced by the engines (varies by flight phase, engine and aircraft type). To make a substantial contribution to airline operating costs, the systems must be lighter and much more efficient.

  We have seen that this is not the case for all systems. However, we have also determined that some of the major power savings do not come from the electrification of the systems themselves, but from the resulting "snowball effects" this can have (e.g. using an EHA concept for landing gear actuation means that the central hydraulic system can be removed. This in turn means that power will be generated only when it is needed, which leads to a saving in fuel use).

- **Effects of Load distribution**. The power required from the systems varies considerably depending on which system is active, and in which flight phase it is active. The landing gear, flaps and slats are prime examples of systems which are only used in particular phases.

  A classical allocation could lead to the over-sizing of some generators, which in turn leads to extra weight carried on-board for generating power which is only used for part of the flight. Balancing all the safety and loading requirements in order to make the generators as small and utilised as possible is thus necessary to realise the full potential of the MEA.
- **Power electronics and drives.** These are a major set of components in the MEA. Consolidating these components, either by standardising them, or specifying their technology, will be one of the future tasks facing an MEA manufacturer and suppliers. The move to solid-state electronics is a must. The packaging and cooling of electronics, and most significantly their reliability, is playing an ever greater role in the feasibility of MEA.

7 Conclusion

The conclusions of the effects of and to some of the systems of an MEA can be seen in sections 5.5 and 6 of this paper. The systems work done by Liebherr-Aerospace for high-lift, landing gear and ECS have been highlighted, but the general conclusions are very similar for most aircraft systems examined.

Initial assessment had indicated that not only is a civil transport MEA in the vein of POA feasible, but achievable within a surprisingly short time span. The launch of the Boeing 7E7, as well as the production of the Airbus A380, now support this. Also of importance is the initial result that despite a potential increase in the weight of major systems, it is possible for an MEA to provide a reduction in fuel usage at the aircraft level. In the end, only this result can lead to the launch of such an MEA, or any aircraft for that matter.

This result is indicative of the inevitably high degree of integration of equipment systems in the MEA, and points the way towards an intensively integrated approach to designing new aircraft. This paper has, however, highlighted that there are many challenges to be met, and some key technologies to be acquired, before a much more electric aircraft becomes commonplace.

8 Acknowledgements

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