THE A380 FLIGHT CONTROL ELECTROHYDROSTATIC ACTUATORS, ACHIEVEMENTS AND LESSONS LEARNT

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Keywords: *More Electric Aircraft, Flight Controls, Actuators, EHA*

Abstract

For a long time the control surfaces of transport airplanes above a certain weight have been hydraulically powered. The most recent generation of in-service commercial transports is showing generalization of the electrical signaling of the hydraulic flight control actuators, known as Fly by Wire(FBW) systems. The very new Airbus product generation, A380 and A400M, now features a mixed flight control actuation power source distribution, associating conventional FBW hydraulic actuators with electrically powered actuators.

On Aug 29, 2005 the A380 flew for the first time with no hydraulics, a world premiere for commercial aviation.

This paper reviews the drivers for this evolution and the selected electrical actuator technology, discusses the achieved A380 flight control electrohydrostatic actuator (EHA) performance and highlights some lessons learnt.

1 The A380 “More Electric” Flight Control Actuation System Configuration

1.1 Control Surfaces

Flight controls of the A380 conventionally include so called “primary flight controls”, dedicated to the control of the roll, yaw and pitch attitudes and of the trajectory of the aircraft, and “secondary flight controls”, also identified as “high lift system”, dedicated to the control of the lift of the wing.

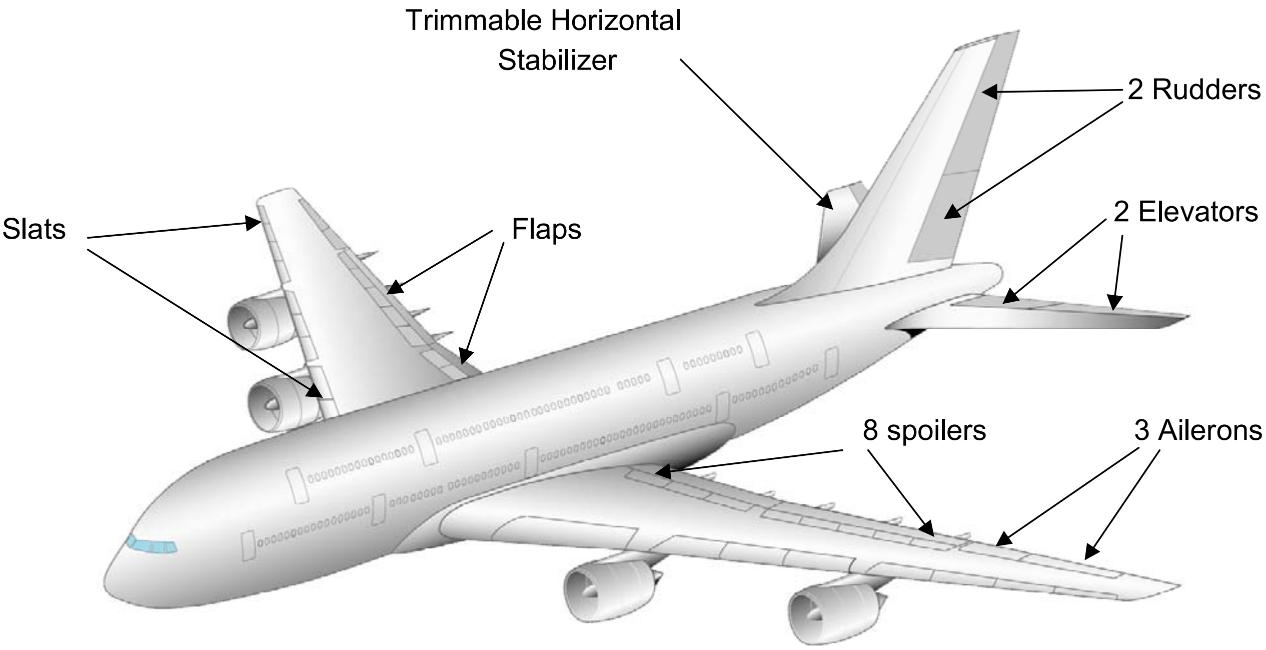

Fig. 1 A380 flight control surfaces

Flight control surfaces are shown in fig.1. Three pairs of ailerons achieve the roll control, a double panel rudder achieves the yaw control and two pairs of elevators and a trimmable horizontal stabilizer achieve the pitch control. Eight pairs of spoilers are provided as speedbrakes and ground spoilers. The six outboard pairs are also operated for complementing the ailerons for roll control. Splitting the aileron in three panels, duplicating rudder and elevator surfaces are primarily intended to cope with the bending of the flexible supporting structures of the wing and empennages of this very large airplane. Additionally they provide more redundancy and make the individual panel failures less critical.

The high lift system includes leading edge slats which generate an aerodynamic effect making possible the use of high angles of attack and trailing edge flaps that basically increase the area an the camber of the wing, and as a consequence the lift provided at a given angle of attack.

1.2 Actuation System Definition Drivers

The architecture of the flight control system, in terms of number of actuators per surface, number and distribution of power sources and flight control computers, is primarily driven by safety considerations.

The safety objectives, as defined by the current regulations, require failures, or combinations of failures, resulting in the loss of the airplane to be demonstrated as Extremely Improbable. This means that their failure rate shall not exceed a probability of 10^{-9} per flight hour.

Complete loss of power supply to a fully powered flight control actuation system, which would result in loss of control, falls in this category. As a consequence the flight control actuation system shall be supplied from several redundant power sources. Practically, taking into account the current reliability of secondary power sources, three independent sources are required.

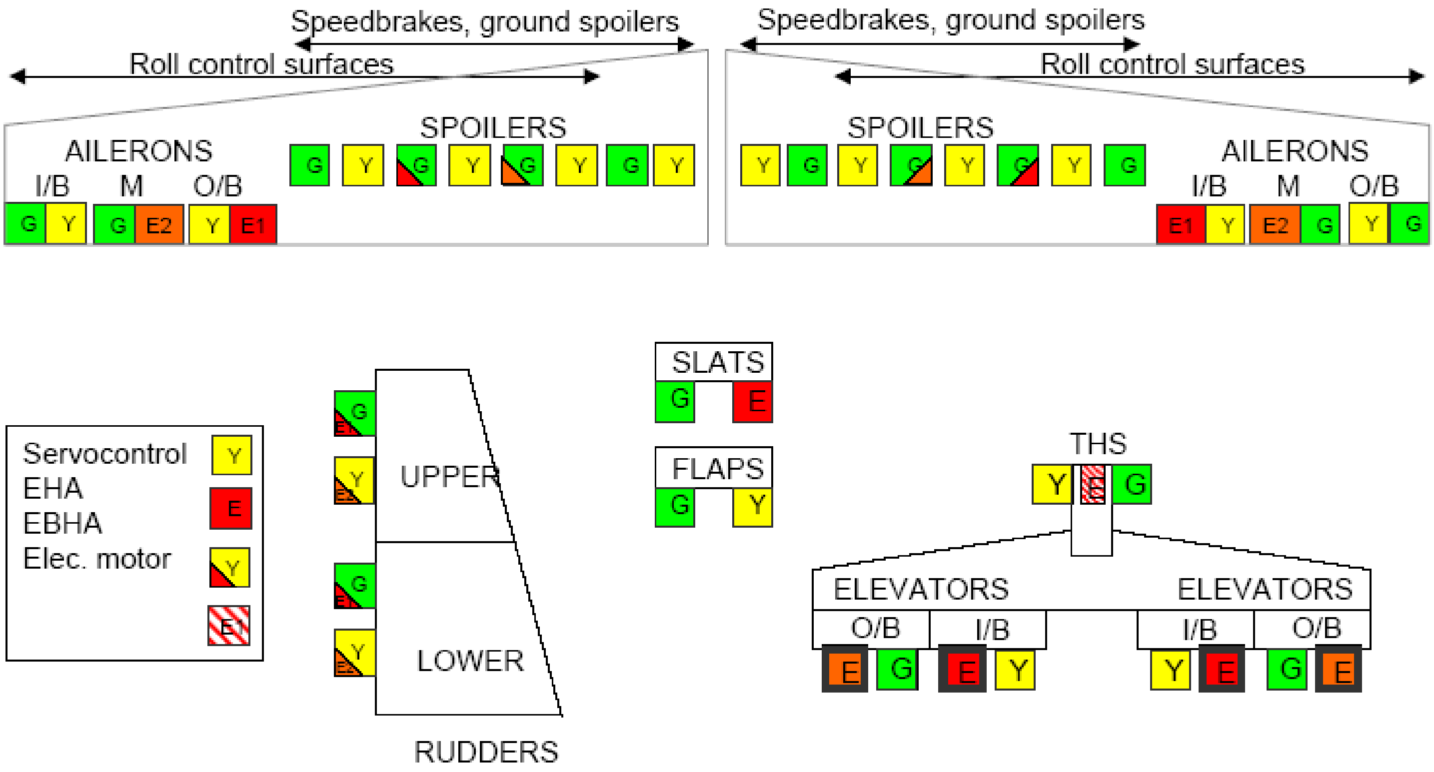

Fig. 2 A380 actuator and power source distribution

Trailing edge control surfaces, if unbalanced, are prone to flutter if left free to rotate, in the event of failure of their driving system. Flutter may be a diverging phenomenon leading to structural rupture. For this reason redundancy of actuation systems and power sources at each trailing edge surface is required, either to keep the loss of control as Extremely Improbable, or to provide damping to the surface in the event of loss of its control, making Extremely Improbable the condition where it would be free to rotate with no damping.

Other safety considerations apply to events identified as "particular risks" which may generate common failure modes to supposedly independent systems: engine or tire burst, mid-air collision with limited structural damage, belong to this category. Geometric segregation of equipment and interconnection routes, introduction of isolation devices are required for minimizing vulnerability to these risks.

Other obviously fundamental criteria are the minimization of the maintenance costs and of the weight of the actuation system and power sources.

1.3 The "2H/2E" Power Source Distribution

As mentioned above 3 independent power sources are required to make the complete loss of the flight control actuation system Extremely Improbable. Conventional commercial transports, including previous Airbus products, are then provided with 3 hydraulic systems, while they are also equipped with 2 main electrical systems for supplying other users, which makes a total of 5 power sources on board.

The A380 "More Electric" flight control actuation concept consists in eliminating one hydraulic system and replacing it with a set of electrically powered actuators, with no detrimental impact to the probability of loosing the flight control actuation system.

The selected power source distribution, identified as "2H/2E", features two hydraulic systems, so called Green and Yellow, and two electric systems, E1 and E2, as shown in Fig 2.

The hydraulic actuators are normally active while the electrically powered actuators are normally stand-by and become operative in the event of a failure of the normal, hydraulically supplied, control lane.

1.4 Benefits of the 2H / 2E Arrangement

Benefits of the introduction of the electrically powered actuators in this "More Electric" architecture are identified in several areas:

In terms of safety several aspects can be highlighted: As far as power source redundancy is concerned the number is increased from 3 to 4 since 2 electrical systems replace 1 hydraulic system. Furthermore an additional margin of safety results from the introduction of the hydraulic/electric dissimilarity in the power sources: This provides further protection against common failures, such as maintenance errors, which may affect all the hydraulic systems, whatever their number. Moreover the electrical power provides flexibility in routing, resulting in an easier segregation of power distribution routes against engine burst and other "particular risks", and an isolation and reconfiguration capability that hydraulic systems cannot offer.

The reduction in the total number of hydraulic components results in improvements of the MTBF and dispatch reliability, by elimination of potential leakage sources.

The elimination of the generation and distribution components associated to one of the hydraulic systems (pump, reservoir, filters, plumbing…) and the replacement of the associated hydraulic actuators by electrically powered actuators results in weight savings.

2 The A380 Electrically Powered Actuators and their Challenges

2.1 EHA and EBHA

The selected type of electrically powered actuator is the Electrohydrostatic Actuator (EHA). As shown in Fig. 3, it is basically a self contained hydraulic actuator incorporating a pump driven by a variable speed electric motor; by transferring back and forth the fluid from one cylinder chamber to the other, the pump and electric motor achieve the control of the position of the piston connected to the surface.

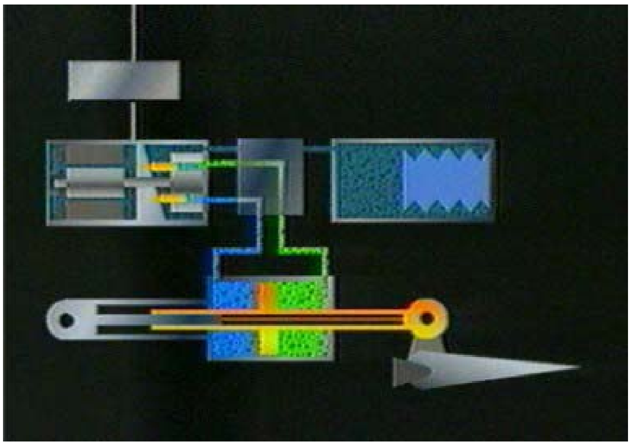

Fig. 3 Electrohydrostatic Actuator principle

In some circumstances it may be beneficial to power a given actuator either from a hydraulic system, like a regular hydraulic actuator, or from an electric system like an EHA. This is the purpose of the Electrical Back-up Actuator (EBHA), that gathers around a common cylinder and piston assembly the servovalve of the hydraulic actuator or "FBW servocontrol" and the motor pump of the EHA as shown in Fig 4.

2.2 EHA versus EMA

Electrohydrostatic actuators are basically electrically powered actuators in which gearing and transmission are hydraulically achieved. Electromechanical actuators (EMA), in which the motor torque is mechanically amplified and transmitted to the control surface, using a gear set, a screw or other mechanical transmission devices could be seen as a better alternative

As far as complexity, weight, reliability, maintenance requirement are concerned, EMA are potentially more attractive than EHA, at least for low power applications. In particular, all hydraulic technology relevant problems are obviously eliminated from the EHA configuration. However in the three following areas EHA are still preferable to EMA:

- The jamming probability of an EMA used in a primary flight control application is difficult to predict and substantiate from existing in-service experience. Jamming probability of an EHA, can be directly assessed from the current hydraulic actuator experience, and shown as Extremely Improbable if properly by-passed. The jamming probability of mechanical systems incorporating hundreds of gear teeth and screw mechanisms is more a question mark and current experience in secondary flight control applications may not be directly transferable to primary flight controls, due to very different duty cycles in particular.

- The same applies to the prediction of the wear life. Wear of the mechanical transmissions components may result in control surface free-play or other non-linearity, which may generate unacceptable limit cycles.

- The introduction of EHA in parallel with regular hydraulic actuator in the basic More Electric architecture described above is easier than EMA. EHA can easily be made reversible in stand-by mode, they can incorporate identical damping devices to those currently used for flutter protection, they can be built with many components that are common with the adjacent hydraulic actuator such as the piston, cylinder, associated position transducer or the accumulator.

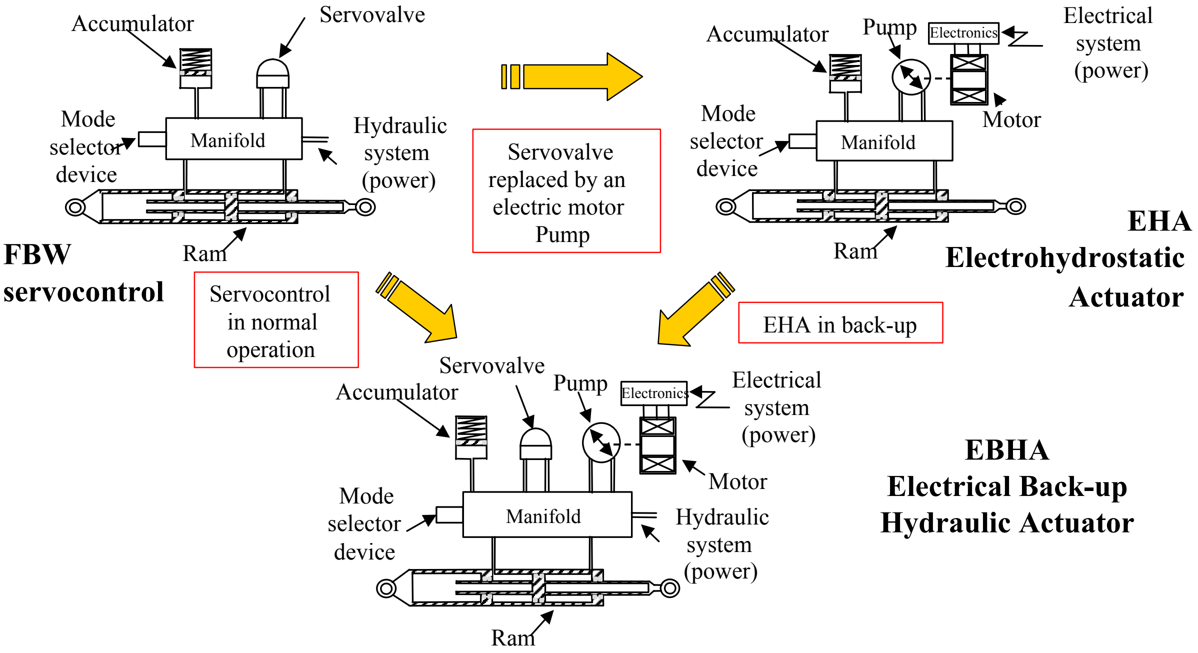

Fig.4 FBW hydraulic actuator, EHA and EBHA

2.3 The EHA/EBHA Technical Challenges

The EHA cannot be considered as the simple interconnection of well known off-the-shelf components, cylinder, pump, electric motor and power electronics. The integration of these components as well as the way they are used to operate an EHA generate unique problems:

The pump: performance and life: Pre-existing aerospace pumps were relatively large displacement pumps, most of the time designed to rotate at constant speed in one direction, with standard efficiency requirements. EHA require high speed, low displacement pumps, capable of high frequency reversals, with extremely reduced losses, because of the low thermal exchange capability of the unit, and showing a decent life under a primary flight control duty cycle.

The electric motor: efficiency and fire risk: The main driver to integrate the pump and electric motor is the elimination of the dynamic shaft seal, which is known as a low reliability item even in a single direction, constant speed application. The motor is then to be designed as a "wet" motor with several possible configurations: Either the rotor only is in contact with the fluid, the stator being isolated by a sealed sleeve filling the air gap, or the stator as well could be in the fluid, allowing a reduced air gap and better performance. The drawback would be the increased fire risk due to the immersion of the stator windings in the hydraulic fluid

The power electronics: packaging and reliability: Electronic controllers are required to be integrated to the actuators or to be installed nearby, in unpressurized areas. Since they are predicted to be the less reliable sub-assembly of the actuator, they are to be designed as Line Replaceable Units (LRU) which makes possible their removal/installation in situ, with no removal of the complete actuator and no adjustment operations

Potential difficulties are then sealing against moisture ingress, explosion and fire containment, nuisance interaction between signal and high power components.

The heat rejection problem: a specification issue and the flight test driver: There is very little thermal concern with conventional flight control/hydraulic system architecture. It is often required to provide some heating at the actuators, excessive heat that may be produced is rejected through the fluid, and most of the time the natural heat exchange capability of the tubing is sufficient to keep the system temperature at the appropriate level.

EHA do produce heat to react surface load, even with no movement, at zero output mechanical power. EHA are self-contained systems with little natural heat exchange capability: forced convection, which would be detrimental to efficiency or result in a drag penalty is avoided, or to be minimized, conduction through the attachments is limited.

Collection of thermal data for the validation of thermal analyses and establishing the capability for future thermal predictions is then the first driver for flight-testing. This is the only technical aspect that could not be fully covered by ground tests.

The cold start. When used in stand-by position, the fluid circulating through the first stage of their servovalve heats FBW hydraulic actuators. Stand-by EHA may have to start up under cruise temperature, -55°C, and reach quickly nominal performance. A permanent heating device may be necessary.

2 The A380 EHA/EBHA Achievements and Lessons Learnt

The end of 2006 plans certification of the A380 and first delivery. Although the development is not fully completed at time to release this paper, a preliminary evaluation can be made, covering the main aspects of the EHA/EBHA design and validation activities.

3.1 Specification

To cover the thermal aspect new sets of specification requirements and data have been developed, on top of the standard data and requirements applicable to conventional FBW hydraulic actuators. They consist in associating mechanical requirements with environmental and time related data. In addition to peak or continuous power requirements the specification should mention "worst case" scenarios as operational sequences or series of sequences identified as sizing cases in terms of heat generated. Duty cycle data reduction, which is conventionally based on fatigue or wear life methodology, shall be reconsidered on the basis of thermal considerations.

3.2 Design and installation

Two EHA, aileron and elevator and two EBHA, rudder and spoiler, have been designed. Two equipment manufacturers were involved, Goodrich Actuation Systems in charge of the aileron, elevator and rudder actuators and Liebherr Aerospace in charge of the spoiler.

The main design driver has been the space envelope, taking into account the requirement to install the motor drive electronics on the unit, mechanically and electrically interfaced as a LRU. One of the equipment manufacturers had to completely redesign the electronic box because of the incorrect internal packaging.

Fig. 5 Aileron EHA and hydraulic actuator

Aileron, elevator and rudder units incorporate equal area piston and cylinder assemblies, while the spoiler EBHA uses an unequal area assy.

The motors have been designed with a wet rotor configuration, a sealed sleeve, sized for withstanding the system pressure, filling the air gap.

3.3 Performance and life

The power efficiency is a key parameter, because of its impacts in terms of heat rejection and power requirement for the Ram Air Turbine that provides the power to the EHA/EBHA in the event of total engine flame out. The pump design has been iterated several times to optimize the volumetric efficiency, which can be measured as the rpm required to hold a given output load, to finally reach approx 1% of the max rate under the stall load of the unit, as new.

Low temperature operation is another key performance: the units have been sized to meet the nominal mechanical requirements at –40°C and to have the capability to start up at –55°C with no additional heating device. This has been achieved, showing overall efficiencies around 50% at –40°C and 75% at ambient, at 50% of the max power.

The dynamic performance for small amplitude inputs is even better than the hydraulic actuators, showing a bandwidth of approx 1.5Hz versus 1 Hz, the control loops being tuned for meeting the same stability margins.

Weight has been permanently challenged during the design phase and is believed to be minimum. Although the weight of the EHA is twice the weight of the adjacent hydraulic actuator, the elimination of one hydraulic system results in a very significant overall weight saving.

Life is limited by the pump wear, which results in a reduction of the volumetric efficiency and increase of the heat rejection. Because the EHA and EBHA are back-up actuators that are used only in the event of failure the life strictly required is few percent of the aircraft life. This is met with a considerable margin by the aileron, elevator and rudder actuator, with smaller margins by the spoiler EBHA.

3.4 Development and qualification testing

Development and qualification tests are performed under the vendor responsibility. Development tests included early risk mitigation tests, validating design details sometime prior to PDR, proper HALT tests of the motor drive electronics, combining operation with high temperature and vibration beyond the specification requirement, and similar high severity testing of the motor and the pump.

Most of the qualification testing was similar to hydraulic actuators, with two specific additional tests requiring a high degree of representativity of the tests fixtures: the heat rejections in an environment simulating the aircraft EHA compartment (Fig. 6) and the EMI, the unit being operated under load (Fig. 7).

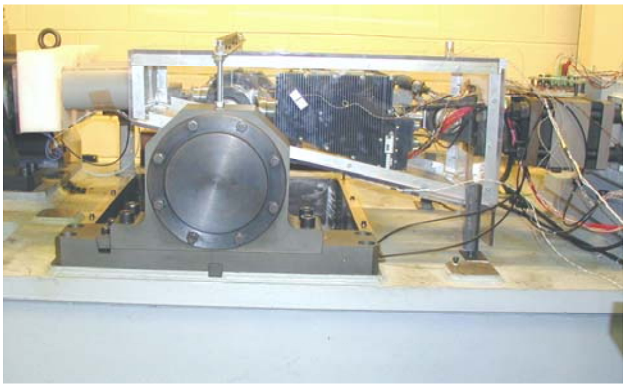

Fig. 6 Heat rejection measurement

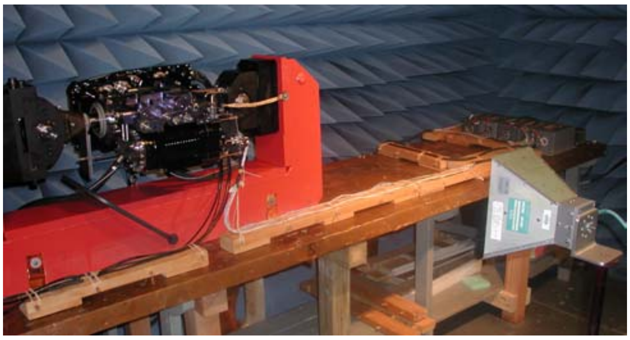

Fig. 7 EMI test under load

One other aspect also differs from the hydraulic actuator testing, which is the limited capability to accelerate endurance tests due to the thermal limitations. Testing an EHA for 20% of the aircraft life requires as much time as testing a hydraulic actuator for 100%.

3.5 Integration testing

Beyond what is required for the validation of the system integration of the hydraulic actuators, the Iron bird testing was also intended to validate the coupling of the full set of EHA and EBHA with the electrical generation. This required all the EHA and EBHA of the Iron Bird, which was not a standard Airbus practice. This was achieved using torsion bars for simulating the air loads at each actuator station (Fig. 8)

Fig. 8 Iron Bird air load simulation

The Iron Bird thermal environment is not representative of the aircraft in flight and it has been shown that unrealistic severe control surface movements such as frequency response may become damaging under these loaded conditions.

3.6 Flight testing

Three test airplanes are currently flying twice a day, having accumulated more than 1500 flying hours up to now. On Aug 29, 2005 the A380 n°1 flew for the first time simulating the dual hydraulic system failure, the control surfaces being driven by the EHA and EBHA, with no significant difference in the aircraft behavior.

Since then, it has been taken opportunity of the long flights, such as Toulouse to Singapore, to artificially activate the EHA and EBHA for accumulating hours of in-flight operation and collecting thermal data.

The cold weather campaign in northern Canada showed nominal operation. The data collected during the intermediate hot weather campaign in southeastern Asia has shown that the aileron EHA, which are the most permanently loaded actuators, require some extra cooling for meeting the objective of operation under ISA+35°C conditions. This was identified as a risk since the beginning of the program; the planned ventilation provision will be implemented and tested with the final hot weather campaign.

3.7 Certification

The EHA and EBHA have not required any specific new regulation, “special conditions” or “issue papers”. The main difference with hydraulic actuators is the demonstration of explosion proofness, some of these actuators being installed in zones adjacent to fuel tanks. Tests have shown that no external sparks or skin temperature beyond 200°C are generated, neither in normal operation, nor under failure condition.

Summary

The A380 features a “More Electric”, hybrid flight control actuation power source distribution, associating a very new concept of electrically powered actuators with conventional FBW hydraulic actuators.

The development of these Electrohydrostatic Actuators timely addressed the technical challenges of this new technology in terms of specification, design and validation, developing a new specific methodology in parallel with the equipment.

The most significant problems encountered were the redesign of the power electronics of the aileron, elevator and rudder units, and the implementation of extra cooling of the aileron EHA.

The A380 is now the first commercial transport that offers to the operators and passengers the performance and weight benefits associated to a reduced number of centralized hydraulic systems, together with the added margin of safety provided by more reliable and dissimilar flight control actuation system power sources.