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The Development of a Highly Reliable Power Management and Distribution System for Civil Transport Aircraft

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THE DEVELOPMENT OF A HIGHLY RELIABLE POWER MANAGEMENT AND DISTRIBUTION SYSTEM FOR CIVIL TRANSPORT AIRCRAFT

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SUMMARY

NASA is pursuing a program in Advanced Subsonic Transport (AST) to develop the technology for a highly reliable Fly-By-Light / Power-By-Wire aircraft. One of the primary objectives of the program is to develop the technology base for confident application of integrated PBW components and systems to transport aircraft to improve operating reliability and efficiency. Technology will be developed so that the present hydraulic and pneumatic systems of the aircraft can be systematically eliminated and replaced by electrical systems. These motor driven actuators would move the aircraft wing surfaces as well as the rudder to provide steering controls for the pilot. Existing aircraft electrical systems are not flight critical and are prone to failure due to Electromagnetic Interference (EMI) (1), ground faults and component failures. In order to successfully implement electromechanical flight control actuation, a Power Management and Distribution (PMAD) System must be designed having a reliability of 1 failure in 10^{+9} hours, EMI hardening and a fault tolerant architecture to ensure uninterrupted power to all aircraft flight critical systems.

The focus of this paper is to analyze, define, and describe technically challenging areas associated with the development of a Power By Wire Aircraft and typical requirements to be established at the box level. The authors will attempt to propose areas of investigation, citing specific military standards and requirements that need to be revised to accommodate the "More Electric Aircraft Systems".

INTRODUCTION

As electrohydraulic and electromechanical actuators replace conventional hydraulically driven effectors on the spoilers, flaps, and rudders of US commercial aircraft, the source of power of these actuators will increasingly become flight critical. The source of electrical power and the PMAD System must be highly reliable and capable of delivering high quality uninterrupted electrical power to the flight critical loads. Flight critical loads are those systems whose continued operation is necessary in order to have sustained safe operation of the aircraft while it is airborne. These loads must remain operational, if for example, the aircraft is struck by lightning or exposed to high intensity radiated fields (HIRF).

Box level qualification procedures must be established which both adequately describe the threats, and assure that adequate margins remain to ensure continued safe operation during a threat occurrence.

This paper will identify specific problem areas to be solved in the PBW program and typical requirements to be established at the box level. Proposed amendments to existing standards and test procedures will be discussed.

Feasibility Issues

Many technical issues must be addressed in order to realize the potential of Fly-By-Light (FBL) and Power-By-Wire (PBW) systems. To ensure the safety of crew and passengers these systems will be required to meet reliability probabilities of 1 failure in 10^{+9} hours of operation. The design of these systems must be inherently fault tolerant. In the event that equipment failures or electrical faults on the distribution bus occur, the PMAD system must autonomously reconfigure and continue to supply electrical power to flight critical electrical loads.

Some examples of flight critical loads would be the flight control computer, the electrical actuators and their respective controllers. In the event that a source fault occurs, non-essential loads must immediately be shed and the system must be reconfigured to supply critical loads from alternate sources. During normal operation established power quality levels will be maintained, but during abnormal operation system bus voltages and frequencies may vary from their nominal values by a predetermined amount. The acceptability and impact of this occurrence must be balanced against the input tolerances of the avionics equipment.

The electrical system must be designed in such a manner that faults occurring in one part of the system cannot propagate throughout the system affecting other electrical loads.

Fault Tolerant Requirements

In order to meet the established PBW aircraft reliability requirements, a highly reliable redundant PMAD system will be required to supply electrical power to flight critical loads. Once this system is designed it must be carefully tested and validated as flight worthy. Extensive testing will be required to establish a specific reliability at a certain confidence level.

Redundancy involves designing one or more alternate signal paths into the system through the addition of parallel elements. A number of approaches are available to improve reliability through redundant design. Redundant design approaches can be classified on the basis of how the redundant elements are introduced into the circuit to provide a parallel signal or power path.

The results of numerous data collection efforts have shown that the reliability of fielded equipment and systems is degraded from three to ten times the potential predicted reliability during design.(2) The transition from paper design, to production, to field operations introduces degradation factors which constrain the expected reliability.

There are two major classes of redundancy: Active and Standby. In active redundant systems external components are not required to perform the functions of detection or making the decision of when to switch to a standby element when the primary path fails. In standby redundant systems, external elements are required to detect a failure condition and to make the decision to switch to a secondary path to bypass the failed element.

Another form of redundancy can exist in addition to the two major classes stated above. This form uses parallel paths within normal non-redundant design configurations. Parallel paths within a network would be sized to carry the added load when an element failure in another parallel path occurs. (3)

Derating can be defined as the operation of a part at less severe stresses than those for which it is rated. Derating can be accomplished by either reducing stresses or by increasing the strength of the part. Selecting a part of greater strength is usually the most practical approach. The failure rate of the part tends to decrease as the applied stress levels are decreased below the rated value. As higher stresses and temperatures are applied to a given part its failure rate increases proportionally. (4)

Reliability is strongly dependent upon the operating conditions that are encountered during the entire life of the equipment. High temperature imposes a severe stress on electronic components since it can cause failure due to the melting of solder joints and slow deterioration of performance levels due to chemical degradation effects. Thermal shock is the effect of varying the temperature of a component over extreme ranges in a short period. The result is over-stressing of the device resulting in cracks, mechanical failures and ultimately changed electrical properties.(3)

A range of environmental stresses play a role in how well a device meets the required specifications. Examples of environmental stresses are high and low temperatures, thermal shock, mechanical shock, vibration, humidity, salt atmosphere and spray, electromagnetic radiation, nuclear / cosmic radiation, sand, dust and low pressure due to high altitude.

An operational experiment could be conducted by performing a large number of trials to establish high-reliability at a high confidence level. If this is not acceptable due to time and cost, a simulated life experiment could begin with a natural life experiment and be augmented by using probability and design arguments. In order to meet a high reliability requirement, an equally high confidence level for the system test experiment is required. If the system can successfully complete a large number of trials without failure, then the system can be said to have the required reliability at the required confidence level. Using a probability formula, one may calculate the required number of trials to achieve a given confidence level. (5) Achieving a reliable confidence level of 1 failure in $1x10^9$ trials would require $21x10^9$ successful trials. This large number of trials can be reduced to a manageable level by using statistics, injecting faults during test trials, and monitoring of the fault tolerant system during testing. Using these approaches, a validation procedure could be developed for a class of fault tolerant systems which will ensure that the target systems can achieve a high degree of reliability through reconfiguration and periodic maintenance.

To support system validation hybrid (analog and digital) computers may be used to perform system simulations, set tolerances and instrumentation ranges, simulate Failure Effects Mode Analysis (FEMA) results, and further support the analysis phase of a systems reliability estimate.

EMI / HIRF Requirements & System Certification

The FBL / PBW PMAD system, the flight control and other aircraft flight critical systems must be immune to EMI and HIRF energy. During these events, the PMAD system must continue to operate nominally and meet minimum power quality requirements.

The Society of Automotive Engineers (SAE) fall 1993 meeting of the AE-7D panel discussed limits for input current harmonics associated with AC input power conversion (utilization) equipment. Preliminary specifications establishing limits on input current harmonics are being circulated for review by utilization equipment manufacturers. Specifications targeted for revision include MIL - STD - 1399 Section 300A (NAVY), Boeing commercial aircraft specifications and IEC 555-2. These new limits will reduce the amount of current harmonics that equipment may conduct into the aircraft electrical system thus improving overall power quality of the system.

In March of 1990 the Department of Transportation issued an Advisory Circular addressing the protection of aircraft electrical and electronic systems against the indirect effects of lightning. The document provides acceptance criteria and protection levels (hardening approaches) against the indirect effects of lightning, its effects on equipment and associated wiring that is mounted on the aircraft interior and exterior.

Sources of EMI due to portable electronics inside the aircraft (carried on by passengers) have been identified. (6) Actions are presently being taken by the Radio Technical Commission for Aeronautics (RTCA) to prevent interference with on-board instrumentation. These actions include the forming of a sub-committee (SC-177) by the RTCA that will address these issues and form a resolution. The sub-committee action plan consists of establishing test methods and criteria, testing of Portable Entertainment Devices (PED), conduction of in-aircraft testing and computer modeling. A final report is due out June 30, 1994.

Line replaceable unit (LRU) level qualification procedures must be established which will enable the certification of the system at the box level thus reducing the overall cost and time invested in PBW system certification. One possible approach would be to use end-to-end system modeling to define the interaction between each LRU and the system. If individual LRU specifications are met, proper system operation should be guaranteed.

Power Quality and Regenerative Power Considerations

Next generation aircraft PMAD systems will be required to both deliver and receive electrical power from a variety of electrical loads while maintaining system power quality within established levels during "normal" system operation. Electric "engine starting" and "emergency" operation are system states that are excluded from "normal" operation power quality requirements. (7) Present power quality requirements, namely distortion spectrum and transient envelopes, must be carefully reviewed to ensure that next generation PMAD design criteria is satisfied.

Regenerative power is the process whereby the overhauling load on a DC motor, or the sudden increase in speed of an AC motor, result in the motor generating a current that is returned to the source bus. Regenerative braking is accomplished by decreasing the inverter frequency to the extent that the corresponding synchronous speed is lower than that of the motor speed. (8) This causes the motor to behave as a generator, converting the mechanical energy to electrical energy which is returned to the source electrical bus. For example, regeneration operation could occur when aircraft surfaces are moved back to their normal positions.

If this regenerative power could be harnessed it could be used to supplement the source power of the electrical bus. However, harnessing this power can prove to be a challenging endeavor. Bi-directional power converters must be utilized to reverse the power flow back onto the source bus or into a shunt resistance, in the event that the source system cannot accept the reverse energy.

Various power converter topologies are being studied that can most efficiently process this regenerated energy. Before this process of recapturing the regenerative energy can be accomplished, however, several technical problems must be resolved. The regenerated power must meet system power quality standards so that it does not cause interference to loads on the source distribution bus. The use of regenerative power will reduce the demand on the primary sources and increase the overall efficiency of the aircraft.

Secondary Power Considerations

Because the primary flight surfaces in a PBW next generation aircraft would be electrically actuated, the nominal electrical power system loading placed on the aircraft will be greater than that of a conventional aircraft. In the event of a primary electrical system failure, a secondary system must be available to supply electrical power to flight critical electrical loads, actuators and controllers.

Emergency sources will be required on next generation aircraft. The options considered must be carefully reviewed and traded off to ensure that the aircraft design goals are satisfied as well as those of the aircraft secondary power system. Examples of secondary electric power presently in use on conventional aircraft are ram air turbine (RAT) and lead acid batteries. Next generation aircraft designers may consider alternative sources of energy for secondary electrical power.

Examples of alternative sources of energy storage could be mechanical (flywheel) batteries or fuel cells. Flywheel batteries, unlike their electrochemical (battery) counterparts, can quickly be recharged and offer a lower weight alternative to conventional batteries. Mechanical batteries store their electrical power in the form of rotational momentum of flywheels. These flywheel batteries are presently in use in Basel, Switzerland supplementing diesel-electric trolleys. (9) Mechanical batteries may prove to be a promising secondary power storage medium due to their ability to quickly absorb transients of regenerated energy from the electrically powered mechanical actuators. This regenerated energy could be quickly stored and supplied to other utilization equipment on the primary or secondary distribution busses.

PBW Enhanced Electrical System Mass vs. Conventional Aircraft System Mass

Trade studies have been conducted to evaluate the weight savings of replacing pneumatic, hydraulic, bleed air and ice protection systems with electrically actuated systems and results have been favorable. The resulting electrical load of an all-electric secondary power system would be much greater than that of a conventional aircraft due to the shifting of loads from pneumatic & hydraulic power to electrical. The PMAD system can be augmented to accommodate the additional electrical loading. Despite the increased electrical loading the overall vehicle weight will be lessened by approximately 2300 pounds on a twin jet commercial aircraft.(10) This lessened weight will translate directly into longer range and lower operating costs for the air carrier.

Military Specifications & FAA Requirements pertaining to the PBW PMAD

Many military specifications are written "open ended" so that they may be tailored to a specific application. Existing aircraft electrical system specifications must be reviewed in detail and amended to recognize external threats, to ensure that future PMAD systems will deliver uninterrupted quality electrical power to flight critical loads. In many instances (i.e., Mil-STD-704), military standards do not accurately define transient and undervoltage testing to adequately represent the threats. This results in the individual loads having to incorporate internal protection and reserve power supplies to sustain equipment through voltage drops on the bus. This increases the weight, complexity and cost of the entire system while lowering its reliability.

Studies have been conducted that indicate that MIL-STD-704 voltage distortion spectrum limits and MIL-STD-461 current limits do not agree. Distortion requirements cited in MIL-STD-704 address electrical power quality requirements that are measured on the aircraft at the connection point of the utilization equipment.(11)

LeRC Role in the FBL/ PBW Program

The FBL/PBW subsonic transport aircraft program is managed at NASA Lewis Research Center by the Advanced Subsonic Technology office in the Aeronautics Directorate. Technical direction and technology development for FBL and PBW are provided by the Instrumentation and Control Technology and Power Technology Divisions, respectively. Primary contractors involved in the program include the Boeing Commercial Aircraft Division and McDonnell Douglas Aerospace Transport Aircraft Division in the FBL and PBW portions, respectively. Program goals include the flight test of optically interfaced controls and electrical actuation technology, a proof of concept PMAD ground test bed, and a starter-generator ground demonstration.

Conclusion

Issues pertaining to the development of a highly reliable electrically actuated aircraft have been addressed. Some of the specifications have been named that will require revision to incorporate the requirements germane to a flight critical PMAD system. In conclusion, the leap from conventional hydraulically driven aircraft systems to Fly-By-Light / Power-By-Wire commercial aircraft systems will be a challenge to airframe designers and engineers. The benefits of reduced bleed air requirements, improved engine efficiency, integral starter/generator technology, electrically driven flight control actuators and environmental control system will result in a more reliable, fuel efficient vehicle for commercial air travel.

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