Fly-by-wire Flight Control Comparative Analysis of Resident and Detached Application Sources of Civil Aircraft

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Abstract—Starting from the current multifunctional integration and architecture design development status of the flight control system for the mainstream civil aircraft, this paper proposes the system design concepts of “In and Out as a Whole”, “Direct Connection and Transmission”, and “Same Sources and Routes” for the external sensors application sources of the flight control system. External application sources are air data, inertial Reference data and angle of attack sensors in this paper, specifically. This paper analyzes and compares the functional residence and separation processing of external application sources for fly-by-wire flight control system. In addition, it demonstrates the correctness of this design concept and its practical engineering value, systematically. This work has provided a significant reference for future civil aircraft design.

1. Introduction
With the development and successful application of fly-by-wire technologies, the flight control system is moving towards the integration trends in functions and controls. In terms of the functions, the flight control system has developed from the initial simple control functions to the current complex functions, which includes basic primary flight control functions and complex functions integrated with auto pilot functions, high lift functions, auto throttle and auto landing functions. In terms of the controls, it has developed from the decentralized control to the integrated control, which a set of software and hardware platforms can complete the integration of the above all functions, so that the system has better economy and maintenance performance. Therefore, the architectural design of civil aircraft flight control systems is becoming more and more complex. In the previous design, the systems were independent, and only the system interfaces needed to be defined. Each system was designed by itself, and finally integrated into the aircraft to achieve the expected functions. While with the improvement of the flight control system integration, the architectural design of the flight control system considers not only the system level design requirements, but also the impact on the aircraft after the integration with other systems. This is the case that the solution is suitable for the system, but unfavorable for the aircraft. Therefore, the flight control system design need to be considered both at the system level and the aircraft level to ensure the overall optimization of the aircraft design.

At present, the mainstream civil aircraft mainly adopt two comprehensive modes: small integrated mode and large integrated mode. The small integrated mode is represented by B7J7, A320, A330 and A340. The outer loop functions of their flight control systems are combined into the flight management guidance computer. And the primary/secondary fly-by-wire flight control computers are configured separately. While the large integrated mode is represented by the B787, using high-speed processors and the separated fly-by-wire flight control computers. The flight control computers integrate Auto Flight
System, High Lift System, Air Data System (ADS) and Inertial Reference System (IRS) functions. In order to achieve the integration, the flight control system only needs to increase the CPU processing capacities by 5% to 10% on the basis of its own needs, thereby meeting the system computing requirements. The benefits are reduced system latency, increased system synchronization, bus structure complexity reduction, weight reduction, volume reduction, more reasonable signal flow and so on.

For the integrated Flight control system of B787 and the Airbus aircraft with Air Data/Inertial Reference Units (ADRIU) [1], ADS, angle of attack (AOA) and IRS are developed as a whole. These aircraft are all following the system design concepts of “In and Out as a Whole”, “Direct Connection and Transmission”, and “Same Sources and Routes”. Any single separate development will result in increased system latency, poor system synchronization, more complex bus structures and signal flows, increased system weight, reduced availability and integrity and so on.

2. Comparative Analysis for External sensors of Flight Control System

Comparative analysis is adapted to help make any decisions throughout the product life cycle, by defining the performance, cost, risk, schedule and other factors of different solutions, their impact weights and correlation factors [2]. The most suitable and acceptable solutions are analyzed and judged according to the needs and constraints. In engineering practice, comparative analysis is applied to the selection of different product scenarios. And the comparative index include weight, interfaces, performance, reliability, development cycles, human factors, development risks, costs, installation layout, technical risks, specific safety risks, internal and external environment manufacturing, energy consumption, maintenance and so on. This paper follows the system design concept of “In and Out as a Whole”, “Direct Connection and Transmission”, and “Same Sources and Routes”.

The ADS collects the inputs from static pressure probes, pressure probes, static pressure holes and total temperature sensors [3]. After calculations and voting by the atmospheric data application software, the outputs such as altitudes, air speed and vertical speed are transmitted to the display systems, flight control systems, flight management systems, cabin pressurization systems and other systems. IRS and AOA are used for critical functions, such as stabilization, high angle of attack protection and so on. The comparative analysis for these external sensors applications as follows.

a) Proposal 1: the flight control computer integrated with external signals processing functions

Figure 1 shows the air data software resided inside of the Flight Control Computer (FCC). FCC adopts redundant inputs configuration for important external sensors, such as ADS, IRS and AOA. Theses external signals have been voted and calculated in FCC to ensure the integrity of the signals [4]. For the signal interfaces design, the transmissions of critical data are isolated from the non-critical data, to prevent from the interference. Also, it is as far as possible to obtain data directly from the sensors, to reduce the data transmission links and ensure the signal availability and integrity.
b) Proposal 2: the detached air data computer and FCC

Figure 2 shows that an independent air data computer (ADC) is used in this proposal. The FCC and ADC acquire the AOA signals from the AOA sensors, respectively. ADC implements the votes algorithm of air data. According to the total temperature, AOA and other signals, ADC calculates and votes the signals, including corrected airspeed, vertical speed, Mach number, attitude, full pressure, static pressure, total atmospheric temperature and static temperature, and then provides these signals to the FCC.

2.1. Mainstream civil aircraft similarity
Comparing with the mainstream civil aircraft in service, it can be seen that flight control systems design is becoming more and more integrated, as Proposal 1. Using ADIRU, A320 integrates air data, IRS, and AOA into the same platform. Similar to A320, A350 uses ADIRU and follows the same technical path by making further technical improvements in the signal usability, integrity, consistency and real-time aspects. Airbus's The independent ADRIU architecture of Airbus adapts the concept of “Direct Connection and Transmission” without the other conversion device. In addition, The ADS of the B787 resides in the flight control system. Considering the close relationship among IRS, ADS and AOA, whether it is a resident architecture or a detached architecture, these three devices are integrated into the same platform as a whole.

2.2. Weight
The weight is an important factor for aircraft development. It impacts the aircraft performance, safety and economy. In contrast to Proposal 1, Proposal 2 has added ADCs. Combined with the overall layout of the aircraft and the regional safety analysis, a suitable location on the aircraft need be selected to install ADC. Then, according to the installation positions of ADCs, new added weights in Proposal 2 are as follows.

a) ADCs;
b) ADC power cables;
c) Signal buses among ADCs;
d) Signal buses between ADC and FCC;
e) Signal buses between AOA sensor and ADC;
f) Signal buses between ADC and the interfaced systems.

2.3. Latency analysis
Latency analysis needs to consider multiple factors for the entire signal transmission links, including the signal modulation and demodulation of the external sensors, bus transmission delay, signal correction delay, calculation delay, computer sampling frequency and other factors [5]. Compared to Proposal 1,
Proposal 2 has increased the ADC sampling time and ADC-to-FCC bus transmission delay over the entire signal transmission link. Figure 3 shows that the entire transmission delay requirements need to be considered from the AOA sensor to the ADS signal output. Both Architecture Proposals should ensure to meet the delay requirements for the entire link.

Figure 3 Time Delay Analysis

2.4. The rationality of the signal flow

2.4.1 Mutually corrective relationship between the signals

IRS, AOA and air data signals have a mutually corrective relationship with each other, and should be configured as a whole, “In and Out as a Whole”. Based on the initial AOA signals from AOA sensor, the body AOA signal is calculated with some correction factors, such as flap angle, landing gear signals, Mach number, pitch rate, air pressure height, airspeed, radio altitude and so on. Th body AOA is used for Static Source Error Correction (SSEC) inside ADC and flight control law inside FCC. Also, some other systems receive the body AOA from FCC and ADC, such as high lift system, display system, recording system, comprehensive monitoring system, maintenance system and so on.

The IRS provides important parameters such as attitude, heading (including magnetic heading and true heading), real-time position information, and acceleration, and the IRS data is voted out through FCC for critical functions such as AOA solution correction, SSEC correction work, and control law calculation.

The ADC adopts SSEC correction of the air data to compensate for the position error. SSEC correction requires correction factors, such as flap angle, nose gear status, spoiler, and RAT state, to determine the current states of the aircraft, and to correct for static source errors based on AOA and some parameters calculated in FCC.

In Proposal 1, after receiving the AOA and IRS signals, FCC performs the signal voting and calculation, and sends the voted signals to the air data software partition for SSEC correction and air data calculation. Then, the corrected air data are sent back to the flight control partition for control law calculation and other functions. Taking into account that the inextricable data correction relationship among IRS, AOA and air data, FCC uniformly calculates and corrects the data in Proposal 1.

In Proposal 2, AOA signals are sent to FCC and ADC respectively. The air data are calculated by the ADC and sent to the FCC. FCC receives IRS signal, AOA signal and the voted air data, and performs the voting and calculations of these signals for the control law functions. However, ADC requires the voted IRS signals and corrective factors sent from FCC for AOA voting and SSEC. Therefore, there are problems of Proposal 2 with signal out of sync and inconsistencies in the correction relationship.

2.4.2 Signal consistency

There are many factors affecting signal consistencies, such as different data transmission paths, incomplete intermediate transmission links and the secondary voting processing. Therefore, multiple path transmission requires technical means to ensure its consistency, which has certain technical difficulties.
In Proposal 2, ADC acquires one resolver of each AOA sensor, while the FCC acquires another resolver signal and performs the AOA calculation, separately. There is an error of 0.5 degrees between the two AOA resolver. Therefore, it causes different signal sources for ADC and FCC, which violate the design concept of “Same Sources and Routes”. In addition, the data sent by the ADC to the FCC should be consistent with the same signals sent to the other interfaced systems. Therefore, to achieve “Same Sources and Routes”, the resident architecture is easier than the detached architecture, and the technical difficulty is lower.

In Proposal 1, the IRS, ADS and AOA are s a whole resided in FCC. After valid judgement and voting, FCC uses these signals for its own, and then directly sends to other related systems through buses. It meets the design concept of “Direct Connection and Transmission”, to ensure the data consistency among all related systems. If the data are forwarded to its member systems via other devices, the availability and integrity of the signals need to be further guaranteed. At the same time, critical member systems require second votes, or their redundancy designs need be increased, which will affect the data consistency between systems or computers.

2.5. Signal availability and integrity
Signal availability and integrity for both Proposal 1 and Proposal 2 can be achieved through redundancy management. Using availability and integrity indicators of the air data in Proposal 1 as the design input, the probability rate of a single air data losing the corrected airspeed, Mach number and pressure altitude is 1E-8; the probability rate of providing the uncorrected airspeed, Mach number and pressure altitude is 1E-10. In contrast, for the same safety requirements, Proposal 2 needs to split the requirements into two parts: 1) ADC and 2) FCC. This increases the safety requirements for each part.

There is a problem that both FCC and ADC in Proposal 2 perform AOA solutions. Hypothesis 1: If the AOA signal processed by the ADC is used for the control law calculation and signal correction in FCC. Due to the different algorithms and correction methods in FCC and ADC, it will have an impact on signal availability and integrity. Also, the SSEC function of AOA in ADC will be affected. Hypothesis 2: If the AOA of FCC is only used for comparative monitoring, it may further reduce the availability due to the different AOA thresholds.

2.6. Energy consumption
The design of the flight control system needs to consider the consumption of hydraulic energy and electrical energy. Proposal 2 adds ADC, which needs to consider the power consumption and power selections. Specific energy consumption needs to be quantitatively calculated based on the supplier's capabilities and overall aircraft requirements.

3. Analysis Results
According to each comparative analysis criterion and the corresponding criterion index proposed above, different designers have been arranged to compare Proposal 1 and Proposal 2, and scored them separately. Figure 4 shows the final analysis conclusion. Based on this result, the final proposal 1 has been determined and incorporated into the design baseline.
Through the comparative analysis from the above aspects, it can be clearly seen that Proposal 1 follows the design concept of “In and Out as a Whole”, “Direct Connection and Transmission”, and “Same Sources and Routes”. Proposal 1 is not only consistent with the current mainstream aircraft design, but also of relatively lighter weight and lower energy consumption. At the same time, Proposal 1 meets the requirements of signal availability, integrity, consistency and rationality. Therefore, the score of Proposal 1 is higher than that of Proposal 2.

4. Conclusion
This paper has studied the current comprehensive design technology of air data, IRS and AOA signals required for the fly-by-wire flight control system. It has systematically proposed the design concept of “In and Out as a Whole”, “Direct Connection and Transmission”, and “Same Sources and Routes”. In addition, from the whole aircraft and flight control system design perspective, this paper comprehensively weighs the resident and detached Application Sources of civil aircraft fly-by-wire flight control system. Only air data signal or any signal source is processed independently, which has an impact on the whole aircraft and the flight control system. Through comparative analysis, this paper has further verified the correctness of the design concept that air data, Inertial Reference signal and AOA signal need be configured as a whole. This paper has practical engineering value for ensuring the availability, integrity, real-time and consistency of the external signal sources required for the flight control system. To be mentioned, in the practical engineering, not only technical factors, but also non-technical factors are need to be considered, such as supply chain risk, cost and so on.

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