

THE BASIC ANALYSIS OF CONTROL SYSTEMS ON COMMERCIAL AIRCRAFT

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Summary: This paper is aimed at the differences between the control systems on commercial aircraft. Architecture of the particular control systems is given a closer look and in this way based on the analogy method of control system of commercial aircraft we can apply this knowledge of control systems to flight laboratories of the University of Žilina, which are the part of project “Centre of Excellence for Air Transport” ITMS 26220120065.

Key words: Aerolab, Control systems, Fly-by-wire, Single aisle aircraft, modification of the structure .

INTRODUCTION

Architecture of the particular control systems is given a closer look and in this way based on the analogy method of control system of commercial aircraft we can apply this knowledge of control systems to flight laboratories of the University of Žilina. For purposes of this paper I have selected Boeing B737 and Airbus A320 as typical representatives being equipped with the above mentioned control systems. These two types of aircraft were selected as they are the most common airliners used by air carriers all over the world. This fact ensured sufficient amount of operational data that could be used for the objective comparison of two competitive control systems.

1. AIRCRAFT FLIGHT CONTROL SYSTEMS

Aircraft flight control system is a sophisticated unit which consists of several subsystems.

These are flight control surfaces with the respective cockpit controls connected with each other by means of mechanical, hydraulic or electrical linkages. These systems are necessary to control aircraft's direction and aircraft's speed.

It is also advisable to mention aircraft engine controls that are used for controlling the engines operation and consequently also the aircraft's speed. At the hand of these controls a pilot is able to control and monitor the operation of the aircraft's powerplant and change the speed of the flight when required. It is relevant to mention reverse thrust as it is an effective method for slowing an aircraft down after touch-down. This process reduces length of landing way. This is carried into operation by a temporary diversion of an aircraft engine's exhaust or changing a propeller pitch to a negative angle. In this way, the produced thrust is redirected forward and the deceleration is provided.

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2. BASIC FLIGHT CONTROL SYSTEMS

The movement of the flying control surfaces in response to the movement of the cockpit controls can be achieved in three ground ways:

- mechanically, where interconnection of the control surfaces and the cockpit controls is resolved directly by a system of cables, rods, levers and chains
- hydraulically, where the hydraulic power is necessary for the control surfaces to be moved. The control valve may be operated mechanically
- electrically, where an electrical signal is sent from the cockpit control to the control surface to provide for movement. The particular movement can be achieved hydraulically

3. FLY-BY-WIRE CONTROL SYSTEM

As the electronic era evolved in the 1960s, so did the idea of aircraft with electronic flight-control systems. Wires replacing cables and pushrods gave to the aircraft many benefits.

Fly-by-wire control system (FBW) is currently used on the space shuttles and on military and civil aircraft to make them safer because wires are less vulnerable to damages than the hydraulic lines they replaced, especially in military aircraft which face the battle damages. In addition, specific safety limits (the aircraft's envelope) can be electronically predetermined to avoid unfavourable situations such as inappropriate bank angle. Next reason for using this control system is improvement in manoeuvrability because computers can command more frequent adjustments than a human pilot can and designers could do away with features that made the plane more stable. In this way, the control system enables unstable aircraft, with features such as a negative static margin, an anhedral or a forward swept wing configuration to be safely flown and controlled. The FBW is also more efficient because of the weight reduction as it took up less volume than the mechanical or hydraulic control systems and thus either reduced the fuel required to fly with the extra weight and permitted carrying more passengers or cargo. It also requires less maintenance than the previously mentioned systems which relied on mechanical or hydraulic linkages and direct pilot control. On the top of these advantages, the computerized flight control ensures a smoother ride than a human pilot alone could provide.

On the other hand, the FBW technology is limited in reliability and processing capability of the digital control system. The digital component failure is unpredictable and cannot be detected through routine maintenance programs. As a result, triple or quadruple redundant systems independent of each other are incorporated into the aircraft design when using the FBW technology. More precisely, there are three or four computers in parallel, and three or four separate wires to each control surface. In case, one or two computers crash, the others continue working.

Today's commercial aviation companies such as Boeing and Airbus demonstrate the differences in control theory as Boeing pilots have ultimate control whereas Airbus pilots must fly within limits determined by this FBW control system software. The Airbus series of airliners used full-authority FBW controls began with their A320 series. Afterwards, the Boeing followed with their 777 while the pilots are still allowed to overcome the aircraft's envelope.

To look more deeply, unmanned aerial vehicles and the X-29 military aircraft are examples of how the FBW has enabled uncontrollable designs to be developed into controllable aircraft. In addition, the FBW technology is installed also in the aircraft simulators.

To sum it up, the FBW system actually replaces manual control of the aircraft with an electronic interface. The movements of flight controls are converted to electronic signals, and flight control computers determine how to move the actuators at each control surface to provide the appropriate response. These actuators can be either hydraulic or electric which will be discussed hereinafter.

4. CONTROL SYSTEM ON B737 AIRCRAFT FAMILY

4.1 Boeing B737 NG – Flight control system

The primary flight control system of the Boeing 737 NG aircraft family uses conventional control wheel, column and pedals. These controls are mechanically linked to hydraulic power control units which command the primary flight control surfaces: ailerons, elevators and rudder. The flight controls are powered by redundant hydraulic sources A and B. All the primary flight controls may be operated either by hydraulic system A or B. If required, the ailerons and elevators can be operated manually. In case of the rudder control, the standby hydraulic system may be used if system A and B pressure is not available.

Taking into consideration the secondary flight controls such as high lift devices consisting of trailing edge flaps and leading edge flaps and slats, these are powered by the hydraulic system B. The trailing edge flaps may be operated electrically in the event the hydraulic system B fails. Under certain conditions the leading edge devices are automatically powered by the power transfer unit. These leading edge flaps may be extended using standby hydraulic pressure, as well.

4.1.1 Pilot controls

Pilots keep at their disposal two control columns, two control wheels, two pairs of rudder pedals, speed brake lever, flap lever, stab trim cut-out switches, stab trim override switch, stabilizer trim switches, stabilizer trim wheel, aileron trim switches, rudder trim control, yaw damper switch, alternate flaps master switch, alternate flaps position switch and flight spoilers switches. Via these means are the pilots able to control the aircraft.

Connection between the columns and wheels is solved through transfer mechanisms which allow the pilots to bypass a jammed control surface. There is also a rigid connection between both pairs of the rudder pedals. Actuation of the spoilers may be operated either manually or automatically depending upon the speed brake lever.

4.1.2 Flight control surfaces

Pitch control is provided by two elevators and a movable horizontal stabilizer. Roll control is provided by two ailerons and eight flight spoilers. A single rudder answers for yaw control. During take-off, the rudder becomes aerodynamically effective between speeds of 40 and 60 knots. The trailing and leading edge flaps and slats provide high lift for take-off, approach and landing. The spoilers are used as speed brakes in the air symmetric flight. They

can be also used with a view to destroy lift and increase braking efficiency when on the ground. In case of installed blended winglets, they provide enhanced performance, extended range and increased fuel efficiency.

5. CONTROL SYSTEM ON A320 AIRCRAFT FAMILY

5.1 A320 aircraft family – Flight control system

This section also discusses pilot's input and its transmission from the pilot through whole control system up to deflection of the intended control surface. Following gained information about the Airbus control system, I have created next flowchart which illustrates the mentioned control related information flow described in this chapter. Ground difference between the two mentioned control systems is based on fact that the Airbus commuted the rod system for wires linked to the particular computers. The exchange facilitated weight saving of 200 kg and more. These computers send this command in form of an electric pulse further to the relevant hydraulic system where hydraulic jack is activated in the same way as on the Boeing 737 family. The only controls which maintain mechanically connected with the hydraulic system by the rod system are rudder pedals whereas yaw damping, turn coordination and trim are still electrically ensured. Additionally, mechanically is also solved backup of trimmable horizontal stabilizers. To sum up the Airbus' control principles, the control system is characterized by electric pulses commanded by the deflection of the pilot's sidestick and operated by aircraft computers. The final deflection is provided hydraulically at all events. The following lines go into details of this control system, its backup, as well as its specific.

Evidently, pilot of the A320 aircraft family has on his disposal a sidestick and rudder pedals as primary controls. The sidestick passes signals to the SEC (Spoiler Elevator Computer) and the ELAC (Elevator Aileron Computer). There are three SECs to achieve spoiler control in the control system and two of them are devoted to standby elevator and stabilizer control. The flight control is achieved also by two ELACs which ensure commands of normal elevator and stabilizer and aileron. These two types of computers are required data from two FCDCs (Flight Control Data Concentrators) which send the data further to ECAM and CFDS. From the SEC and ELAC the control related information flow continues to the hydraulic system. When the relevant hydraulic circuit is within the acceptable required frame, hydraulic jack is actuated in order to deflect the appropriate control surface: elevator deflection or aileron and/or spoiler deflection. Typical is an automatic elevator for bank angle compensation up to 33°. In more serious case of low pressure or other problem in the relevant hydraulic circuit, there are two more hydraulic circuits to ensure requisite safety. Generally, two of the three hydraulic circuits are dependent on the two engines and the third one on electrical power. This third circuit, known as blue hydraulic circuit, is connected to RAT (Ram Air Turbine) which is pushed out in case of dual engine failure to ensure electric supply to the blue circuit via transmitting mechanical energy which is a function of airspeed to electrical energy. In this way, the resupplied blue circuit by the RAT can ensure the required hydraulic deflection of the relevant control surface. If the RAT is pushed out, there is need to land at higher speed due to need of higher rotation speed of the RAT during the landing to adequately supply the blue hydraulic system. After touch down when there is obviously

insufficient rotation speed of the RAT, a brake hydraulic backup system is used. This system has energy for eight depresses of the rudder pedals. In this way, braking effect may be sufficiently provided even with the dual-engine failure and inoperative RAT. Slightly different steps follow the rudder pedals input as the pedals are mechanically connected directly to the relevant hydraulic circuit as mentioned hereinbefore which ensure an advantageous backup. On the other hand, information of the pedal deflection goes also to the FAC (Flight Augmentation Computer) via electrical way. There are two FACs in the control system. These computers achieve electrical rudder control and characteristics speeds calculations for displays on PFD.

All of the three types of computers ensure safety to the aircraft. The safety is wasted by „flight envelope“ defined in the computers' software. The „flight“ or „aircraft envelope“ has some specific limitations. For example, according to pitch manoeuvre is the adaptation of normal control law divided into three modes: ground with direct relationship between stick and elevator available before lift-off and after touch-down, take-off for smooth transition, blend of ground phase law and N_z command law over 5 seconds after lift-off and landing where the attitude is memorized as reference pitch attitude at 50ft. In flight, pitch-up angle is allowed up to 30° and pitch-down angle up to 15° . Taking into consideration roll and yaw manoeuvres; there are strict control restrictions where the computers have the last word. In an exemplary way, coordinated roll and yaw deflections are achieved by released stick up to 33° . Bank angle protection is noticed above 33° when positive spiral stability is restored up to 67° inside normal flight envelope and 67° is considered as a bank angle limit. Interesting are procedures in case of engine failure or aircraft asymmetry compensation without any pilot's action consisting of the following supports: stabilized sideslip and bank angle followed by automatic rudder trimming to compensate the asymmetric thrust and slowly diverging heading. The EFCS also allows overspeed protection when positive load factor demand is automatically applied when $V_{mo} + 6kt$ to $M_{mo} + 0.01$ is reached. Speed is limited to $V_{mo} + 16kt$ and $M_{mo} + 0.04$ when full nose-down stick is maintained. In these cases, the bank angle limitation is 45° . Further important limitation is angle of attack ($AOA = \alpha$) protection (prot). Principle of this protection is based on fact that when α becomes greater than α_{prot} , the normal flight control law is replaced by an angle of attack law (angle of attack corresponds to stick displacement). Autotrim stops which result in a nose-down tendency. If α reaches α_{floor} , the auto-thrust system will apply go-around thrust. The α_{max} cannot be exceeded even if the stick is pulled fully back. At $\alpha_{max} + 4^\circ$ an audio stall warning (cricket + synthetic voice) is provided, as well. Regarding the consequences, if α_{prot} is maintained, if sidestick is left neutral, if α_{max} is maintained and if sidestick is deflected fully aft- return to normal law is obtained when sidestick is pushed forward.

6. COMPARISON OF THE CONTROL SYSTEMS ON SINGLE AISLE AIRCRAFT

The ground difference between the Boeing and Airbus control system lies in pilot position. The Boeing control system allows the pilot to have the upper hand over the aircraft control whereas in case of the Airbus control system, the computers have the last word in accordance to the aircraft control. Next Airbus control system divergence from the Boeing'

one lies in control reaction. The Boeing's yoke bar reacts directly to pilot's commands, for example when a pilot pull the control backwards, the aircraft adequately climbs and when the control is subsequently left in its neutral position, the aircraft breaks into horizontal flight. On the other hand, in case the Airbus' sidestick deflection is provided and subsequently returned to its neutral position, this is a command for the aircraft computer to maintain the given deflection and so maintain the appropriate climb disregarding the return of sidestick to its neutral position. The climb is broken in case a next command is ordered in the relevant way. Further difference is mass.

Concerning the gained knowledge as well as conclusions from an interview with a pilot who flies both conventional and fly-by-wire aircraft it can be said that air pilotage involves less work load on pilots in the A320 family than in the B737 NG family. Next there is also a sensational advantage of the A320 aircraft family due to cockpit spaciousness. Despite the A320 family uses the fly-by-wire method which can save 200 kg or more, the B737 NG aircraft family are still lighter. On the other hand, the A320 offers more spacious fuselage which means, as mentioned therein before, more comfort as for passengers so for crew. On the other hand, in the B737 NG family pilot subconsciously feels firm interconnection between his control yoke and relevant control surfaces. This fact often cause higher trust to the conventional control system of the B737 NG family among pilots. Over the way, in case of one engine failure, A320 aircraft family are certificated up to III A ILS approach category and B737 aircraft family are certificated up to approach II ILS category using autopilot.

Generally, irrespective of pros and cons of these two matching types, the B737NG family and the A320 family represent driving units of their companies, and at the same time these aircraft vastly similar to each other hold a position of leaders in world of commercial single aisle twin-engine aircraft.

CONCLUSION

Providing that two such strong and advanced aircraft families are being compared, there are only long odds to objectively claim that right one aircraft family is definitely better. Both the Boeing and the Airbus family have their own benefits and drawbacks. The fact is that from pilot's point of view, the A320 family provides more comfort and less workload to the pilot. This has positive impact on safety of the flight. The safety and reliability is also guaranteed in certification of the aircraft's autopilot to perform an ILS CAT III. An approach in case only one engine is operable. The Boeing 737 is certificated with one engine operable to ILS CAT II. only. On the other hand, as suggested in the chapter 5, it is obvious that the fully-computerized aircraft have also their negative features as misunderstanding on the man-machine interface level may increase pilot's workload in critical situations.

The conclusion of this paper is that despite of the different control architecture of the mentioned aircraft, there is no striking difference in impact on safety in spite of the installed „flight envelope“ on the A320 family. In my opinion, in future both of the companies will use the fly-by-wire or similar fully-computerized method on their aircraft as computerization reflect future of aviation.

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REFERENCES

- (1) MARTY CURRY: F-8 Digital Fly-By-Wire Aircraft, NASA, 2008.
- (2) GALE R. SUNBERG: Civil Air Transport: A Fresh Look at Power-By-Wire and Fly-By-Light, NASA Technical Memorandum 102574, 1990.
- (3) BOWERS, PETER M.: Boeing Aircraft since 1916, Annapolis, Maryland, Naval Institute Press, 1989, ISBN 0870210378.
- (4) ENDRES, GÜNTER: The Illustrated Directory of Modern Commercial Aircraft, Osceola, Wisconsin, MBI Publishing Company, 2001, ISBN 0760311250.
- (5) SHARPE, MICHAEL AND ROBBIE SHAW: Boeing 737-100 and 200, Osceola, Wisconsin, MBI Publishing Company, 2001, ISBN 0760309914.
- (6) MARK NICHOLLS: AIRBUS JETLINERS: The European Solution, Classic Aircraft Series No.6. Stamford, Key Publishing, 2001, ISBN 0946219532.
- (7) Airbus: A320 Flight Crew Operating Manual: Flight Controls, 2001.
- (8) BRANISLAV KANDERA, VOJTĚCH SCHWARZMANN: Controlled flight into terrain In: TRANSCOM 2011 : 9-th European conference of young research and scientific workers : Žilna, June 27-29, 2011, Slovak Republic. - Žilina: University of Žilina, 2011. - ISBN 978-80-554-0369-4.