Fly-by-wire

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Green colored flight control wiring of a test aircraft

Fly-by-wire (FBW) is a system that replaces the conventional manual flight controls of an aircraft with an electronic interface. The movements of flight controls are converted to electronic signals transmitted by wires (hence the fly-by-wire term), and flight control computers determine how to move the actuators at each control surface to provide the ordered response. The fly-by-wire system also allows automatic signals sent by the aircraft's computers to perform functions without the pilot's input, as in systems that automatically help stabilize the aircraft.[1]

Contents

Development

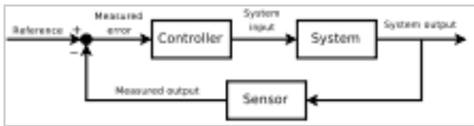
Mechanical and hydro-mechanical flight control systems are relatively heavy and require careful routing of flight control cables through the aircraft by systems of pulleys, cranks, tension cables and hydraulic pipes. Both systems often require redundant backup to deal with failures, which again increases weight. Furthermore, both have limited ability to compensate for changing aerodynamic conditions. Dangerous characteristics such as stalling, spinning and pilot-induced oscillation (PIO), which depend mainly on the stability and structure of the aircraft concerned rather than the control system itself, can still occur with these systems.[*citation needed*]

The term "fly-by-wire" implies a purely electrically-signaled control system. However, it is used in the general sense of computer-configured controls, where a computer system is interposed between the operator and the final control actuators or surfaces. This modifies the manual inputs of the pilot in accordance with control parameters.[1]

Side-sticks, center sticks, or conventional flight control yokes can be used to fly FBW aircraft. While the side-stick offers the advantages of being lighter, mechanically simpler, and unobtrusive, The Boeing Company's aerospace engineers decided that the lack of visual feedback (none given by side-sticks) is a significant problem, and so they designed conventional control yokes in the Boeing 777 and the brand-new Boeing 787, which is undergoing flight tests as of April 2011. This same approach has been used for the Embraer 170/190 jets. Most Airbus airliners are operated with side-sticks.[*citation needed*]

Basic operation

Command



Simple feedback loop

Fly-by wire systems are by their nature quite complex; however their operation can be explained in relatively simple terms. When a pilot moves the control column (or sidestick), a signal is sent to a computer, this is analogous to moving a game controller, the signal is sent through multiple wires (channels) to ensure that the signal reaches the computer. A 'Triplex' is when there are three channels being used. The computer receives the signals, performs a calculation (adds the signal voltages and divides by the number of signals received to find the mean average voltage) and adds another channel. These four 'Quadruplex' signals are then sent to the control surface actuator, and the surface begins to move. Potentiometers in the actuator send a signal back to the computer (usually a negative voltage) reporting the position of the actuator. When the actuator reaches the desired position, the two signals (incoming and outgoing) cancel each other out and the actuator stops moving (completing a feedback loop).[*citation needed*]

Automatic Stability Systems

Fly-by-wire control systems allow aircraft computers to perform tasks without pilot input. Automatic stability systems operate in this way. Gyroscopes fitted with sensors are mounted in an aircraft to sense movement changes in the pitch, roll and yaw axes. Any movement (from straight and level flight for example) results in signals to the computer, which automatically moves control actuators to stabilize the aircraft.[*citation needed*]

Safety and redundancy

Aircraft systems may be quadruplexed (four independent channels) to prevent loss of signals in the case of failure of one or even two channels. High performance aircraft that have FBW controls (also called CCVs or Control-Configured Vehicles) may be deliberately designed to have low or even negative stability in some flight regimes, the rapid-reacting CCV controls compensating for the lack of natural stability.[*citation needed*]

Pre-flight safety checks of a fly-by-wire system are often performed using Built-In Test Equipment (BITE). On programming the system, either by the pilot or groundcrew, a number of control movement steps are automatically performed. Any failure will be indicated to the crews.[*citation needed*]

Some aircraft, the Panavia Tornado for example, retain a very basic hydro-mechanical backup system for limited flight control capability on losing electrical power, in the case of the Tornado this allows rudimentary control of the stabilators only for pitch and roll axis movements.[*citation needed*]

Weight saving

A FBW aircraft can be lighter than a similar design with conventional controls. Partly due to the lower overall weight of the system components; and partly because the natural stability of the aircraft can be relaxed, slightly for a transport aircraft and more for a maneuverable fighter, which means that the stability surfaces that are part of the aircraft structure can therefore be made smaller. These include the vertical and horizontal stabilizers (fin and tailplane) that are (normally) at the rear of the fuselage. If these structures can be reduced in size, airframe weight is reduced. The advantages of FBW controls were first exploited by the military and then in the commercial airline market. The Airbus series of airliners used full-authority FBW controls beginning with their A320 series, see A320 flight control (though some limited FBW functions existed on A310).[2] Boeing followed with their 777 and later designs.

Electronic fly-by-wire systems can respond flexibly to changing aerodynamic conditions, by tailoring flight control surface movements so that aircraft response to control inputs is appropriate to flight conditions. Electronic systems require less maintenance, whereas mechanical and hydraulic systems require lubrication, tension adjustments, leak checks, fluid changes, etc. Furthermore, putting circuitry between pilot and aircraft can enhance safety; for example the control system can try to prevent a stall, or it can stop the pilot from over stressing the airframe.[*citation needed*]

The main concern with fly-by-wire systems is reliability. While traditional mechanical or hydraulic control systems usually fail gradually, the loss of all flight control computers could immediately render the aircraft uncontrollable. For this reason, most fly-by-wire systems incorporate either redundant computers (triplex, quadruplex etc.), some kind of mechanical or hydraulic backup or a combination of both. A "mixed" control system such as the latter is not desirable and modern FBW aircraft normally avoid it by having more independent FBW channels, thereby reducing the possibility of overall failure to minuscule levels that are acceptable to the independent regulatory and safety authority responsible for aircraft design, testing and certification before operational service.[*citation needed*]

History

Electronic signalling of the control surfaces was tested in the 1950s. This replaced long runs of mechanical and hydraulic connections with electrical ones.

The first non-experimental aircraft that was designed and flown (in 1958) with a fly-by-wire flight control system was the Avro Canada CF-105 Arrow.[3][4] a feat not repeated with a production aircraft until the Concorde in 1969. This system also included solid-state components and system redundancy, was designed to be integrated with a computerised navigation and automatic search and track radar, was flyable from ground control with data uplink and downlink, and provided artificial feel (feedback) to the pilot.[4]

F-8C Crusader digital fly-by-wire testbed

In the UK the two seater Avro 707B was flown with a Fairey system with mechanical backup[5] in the early to mid-60s. The programme was curtailed when the airframe ran out of flight time.[6]

The first digital fly-by-wire aircraft without a mechanical backup[7] to take to the air (in 1972) was an F-8 Crusader, which had been modified electronically by the National Aeronautics and Space Administration of the United States as a test aircraft.[8] Control was through a digital computer with three analogue backup channels. In the USSR the Sukhoi T-4 also flew. At about the same time in the United Kingdom a trainer variant of the British Hawker Hunter fighter was modified at the British Royal Aircraft Establishment with fly-by-wire flight controls[6]for the right-seat pilot. This was test-flown, with the left-seat pilot having conventional flight controls for safety reasons, and with the capability for him to override and turn off the fly-by-wire system.[*citation needed*] It flew in April 1972.

Analog systems

All "fly-by-wire" flight control systems eliminate the complexity, the fragility, and the weight of the mechanical circuit of the hydromechanical or electromechanical flight control systems. Fly-by-wire replace those with electronic circuits. The control mechanisms in the cockpit now operate signal transducers, which in turn generate the appropriate electronic commands. These are next processed by an electronic controller, either an analog one, or more modernly, a digital one. Aircraft and spacecraft autopilots are now part of the electronic controller.[*citation needed*]

The hydraulic circuits are similar except that mechanical servo valves are replaced with electrically-controlled servo valves, operated by the electronic controller. This is the simplest and earliest configuration of an analog fly-by-wire flight control system. In this configuration, the flight control systems must simulate "feel". The electronic controller controls electrical feel devices that provide the appropriate "feel" forces on the manual controls. This was used in Concorde, the first production fly-by-wire airliner.[9]

In more sophisticated versions, analog computers replaced the electronic controller. The canceled 1950s Canadian supersonic intercepter, the Avro Canada CF-105 Arrow, employed this type of system. Analog computers also allowed some customization of flight control characteristics, including relaxed stability. This was exploited by the early versions of F-16, giving it impressive maneuverability.[*citation needed*]

Digital systems

A digital fly-by-wire flight control system is similar to its analog counterpart. However, the signal processing is done by digital computers and the pilot literally can "fly-via-computer". This also increases the flexibility of the flight control system, since the digital computers can receive input from any aircraft sensor

The Airbus A320, first airliner with digital fly-by-wire controls

(such as the altimeters and the pitot tubes. This also increases the electronic stability, because the system is less dependent on the values of critical electrical components in an analog controller.[*citation needed*]

The computers sense position and force inputs from pilot controls and aircraft sensors. They solve differential equations to determine the appropriate command signals that move the flight controls to execute the intentions of the pilot.[*citation needed*]

The programming of the digital computers enable flight envelope protection. In this aircraft designers precisely tailor an aircraft's handling characteristics, to stay within the overall limits of what is possible given the aerodynamics and structure of the aircraft. For example, the computer in flight envelope protection mode can try to prevent the aircraft from being handled dangerously by preventing pilots from exceeding preset limits on the aircraft's flight-control envelope, such as those that prevent stalls and spins, and which limit airspeeds and g forces on the airplane. Software can also be included that stabilize the flight-control inputs to avoid pilot-induced oscillations.[*citation needed*]

Since the flight-control computers continuously "fly" the aircraft, pilot's workloads can be reduced. Also, in military and naval applications, it is now possible to fly military aircraft that have relaxed stability. The primary benefit for such aircraft is more maneuverability during combat and training flights, and the so-called "carefree handling" because stalling, spinning and other undesirable performances are prevented automatically by the computers.[*citation needed*]

Digital flight control systems enable inherently unstable combat aircraft, such as the F-117 Nighthawk and the B-2 Spirit flying wing to fly in usable and safe manners.[*citation needed*]

Applications

- The Space Shuttle Orbiter has an all-digital fly-by-wire control system. This system was first exercised (as the only flight control system) during the glider unpowered-flight "Approach and Landing Tests" that began on the Space Shuttle *Enterprise* during 1977.[*citation needed*]
- Launched into production during 1984, the Airbus Industries Airbus A320 became the first airliner to fly with an all-digital fly-by-wire control system.[10]
- During 2005, the Dassault Falcon 7X became the first business jet with fly-by-wire controls.[*citation needed*]

A Dassault Falcon 7X, the first business jet with digital fly-by-wire controls

Legislation

The Federal Aviation Administration (FAA) of the United States has adopted the RTCA/DO-178B, titled "Software Considerations in Airborne Systems and Equipment Certification", as the certification standard for aviation software. Any safety-critical component in a digital fly-by-wire system including applications of the laws of aeronautics and computer operating systems will need to be certified to DO-178B Level A, which is applicable for preventing potential catastrophic failures.[*citation needed*]

Nevertheless, the top concern for computerized, digital, fly-by-wire systems is reliability, even more so than for analog electronic control systems. This is because the digital computers that are running software are often the only control path between the pilot and aircraft's flight control surfaces. If the computer software crashes for any reason, the pilot may be unable to control an aircraft. Hence virtually all fly-by-wire flight control systems are either triply or quadruply redundant in their computers and electronics. These have three or four flight-control computers operating in parallel, and three or four separate data buses connecting them with each control surface.[*citation needed*]

Redundancy

If one of the flight-control computers crashes, or is damaged in combat, or suffers from "insanity" caused by electromagnetic pulses, the others overrule the faulty one (or even two of them), they continue flying the aircraft safely, and they can either turn off or re-boot the faulty computers. Any flight-control computer whose results disagree with the others is ruled to be faulty, and it is either ignored or re-booted. (In other words, it is voted-out of control by the others.)[*citation needed*]

In addition, most of the early digital fly-by-wire aircraft also had an analog electrical, a mechanical, or a hydraulic back-up flight control system. The Space Shuttle has, in addition to its redundant set of four digital computers running its primary flight-control software, a fifth back-up computer running a separately developed, reduced-function, software flight-control system - one that can be commanded to take over in the event that a fault ever affects all of the computers in the other four. This back-up system serves to reduce the risk of total flight-control-system failure ever happening because of a general-purpose flight software fault has escaped notice in the other four computers.[*citation needed*]

For airliners, flight-control redundancy improves their safety, but fly-by-wire control systems also improve economy in flight because they are lighter, and they eliminate the need for many mechanical, and heavy, flight-control mechanisms. Furthermore, most modern airliners have computerized systems that control their jet engine throttles, air inlets, fuel storage and distribution system, in such a way to minimize their consumption of jet fuel. Thus, digital control systems do their best to reduce the cost of flights.[*citation needed*]

Airbus/Boeing

Main article: Flight control modes (electronic)

Airbus and Boeing commercial airplanes differ in their approaches in using fly-by-wire systems. In Airbus airliners, the flight-envelope control system always retains ultimate flight control, and it will not permit the pilots to fly outside these performance limits. However, in the event of multiple failures of redundant computers, the A320 does have mechanical back-up system for its pitch trim and its rudder. The A340-600 has a purely electrical (not electronic) back-up rudder control system, and beginning with the new A380 airliner, all flight-control systems have back-up systems that are purely electrical through the use of a so-called "three-axis Backup Control Module" (BCM)[11]

With the Boeing 777 model airliners, the two pilots can completely override the computerized flight-control system to permit the aircraft to be flown beyond its usual flight-control envelope during emergencies. Airbus's strategy, which began with the Airbus A320, has been continued on subsequent Airbus airliners.[12][13]

Engine digital control

Main article: FADEC

The advent of FADEC (Full Authority Digital Engine Control) engines permits operation of the flight control systems and autothrottles for the engines to be fully integrated. On modern military aircraft other systems such as autostabilization, navigation, radar and weapons system are all integrated with the flight control systems. FADEC allows maximum performance to be extracted from the aircraft without fear of engine misoperation, aircraft damage or high pilot workloads.

In the civil field, the integration increases flight safety and economy. The Airbus A320 and its fly-by-wire brethren are protected from dangerous situations such as low-speed stall or overstressing by flight envelope protection. As a result, in such conditions, the flight control systems commands the engines to increase thrust without pilot intervention. In economy cruise modes, the flight control systems adjust the throttles and fuel tank selections more precisely than all but the most skillful pilots. FADEC reduces rudder drag needed to compensate for sideways flight from unbalanced engine thrust. On the A330/A340 family, fuel is transferred between the main (wing and center fuselage) tanks and a fuel tank in the horizontal stabilizer, to optimize the aircraft's center of gravity during cruise flight. The fuel management controls keep the aircraft's center of gravity accurately trimmed with fuel weight, rather than drag-inducing aerodynamic trims in the elevators.

Further developments

Fly-by-optics

Fly-by-optics is sometimes used instead of fly-by-wire because it can transfer data at higher speeds, and it is immune to electromagnetic interference. In most cases, the cables are just changed from electrical to optical fiber cables. Sometimes it is referred to as "fly-by-light" due to its use of fiber optics. The data generated by the software and interpreted by the controller remain the same.

Power-by-wire

Having eliminated the mechanical transmission circuits in fly-by-wire flight control systems, the next step is to eliminate the bulky and heavy hydraulic circuits. The hydraulic circuit is replaced by an electrical power circuit. The power circuits power electrical or self-contained electrohydraulic actuators that are controlled by the digital flight control computers. All benefits of digital fly-by-wire are retained.

The biggest benefits are weight savings, the possibility of redundant power circuits and tighter integration between the aircraft flight control systems and its avionics systems. The absence of hydraulics greatly reduces maintenance costs. This system is used in the Lockheed Martin F-35 Lightning II and in Airbus A380 backup flight controls. The Boeing 787 will also incorporate some electrically operated flight controls (spoilers and horizontal stabilizer), which will remain operational with either a total hydraulics failure and/or flight control computer failure.

Fly-by-wireless

Wiring adds a considerable amount of weight to an aircraft; therefore, researchers are exploring implementing fly-by-wireless solutions. Fly-by-wireless systems are very similar to fly-by-wire systems, however, instead of using a wired protocol for the physical layer a wireless protocol is employed.

In addition to reducing weight, implementing a wireless solution has the potential to reduce costs throughout an aircraft's life cycle. For example, many key failure points associated with wire and connectors will be eliminated thus hours spent troubleshooting wires and connectors will be reduced. Furthermore, engineering costs could potentially decrease because less time would be spent on designing wiring installations, late changes in an aircraft's design would be easier to manage, etc.[14]

Intelligent Flight Control System

A newer flight control system, called Intelligent Flight Control System (IFCS), is an extension of modern digital fly-by-wire flight control systems. The aim is to intelligently compensate for aircraft damage and failure during flight, such as automatically using engine thrust and other avionics to compensate for severe failures such as loss of hydraulics, loss of rudder, loss of ailerons, loss of an engine, etc. Several demonstrations were made on a flight simulator where a Cessna-trained small-aircraft pilot successfully landed a heavily-damaged full-size concept jet, without prior experience with large-body jet aircraft. This development is being spearheaded by NASA Dryden Flight Research Center.[15] It is reported that enhancements are mostly software upgrades to existing fully computerized digital fly-by-wire flight control systems.

See also

- Aircraft flight control system
- Flight control modes (electronic)
- MIL-STD-1553, a standard data bus for fly-by-wire
- Relaxed stability

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