Fly-by-wire flight control

by R. P. G. Collinson

Fly-by-wire flight control has enabled a watershed improvement in aircraft performance and control to be achieved. This article covers first the basic concepts of FBW control and key elements such as electrical data transmission, failure survival actuation systems, aircraft motion sensors, and air data systems. Aircraft stability is then briefly described. The unique advantages of FBW control are next covered and roll rate and pitch rate manoeuvre command control explained. Safety and integrity requirements are then discussed together with failure survival redundancy. The architecture and implementation of a quadruplex FBW system is explained. The problem of common-mode failures and the need for dissimilar redundancy are covered and the methods used to achieve dissimilar redundancy described.

The introduction of fly-by-wire (FBW) flight control systems has been a watershed development in aircraft evolution as it has enabled technical advances to be made which were not possible before. One of the unique benefits of a FBW system is the ability to exploit aircraft configurations which provide increased aerodynamic efficiency, like more lift and lower drag, but at a cost of reduced natural stability. This can include negative stability, that is the aircraft is unstable over part of the range of speed and height conditions (or flight envelope).

Aircraft with conventional flight control systems have to be statically stable in pitch. This means that if the aircraft is pitched up (or down) following a disturbance such as a gust, the resulting aerodynamic forces will restore the aircraft to its original pitch attitude without any action by the pilot—that is, the control surfaces are 'passive'.

If the aircraft is aerodynamically unstable, however, the slightest disturbance will cause the aircraft flight path to diverge rapidly in pitch. The rapidly increasing '*g*' forces which result will cause catastrophic structural failure of the aircraft unless the divergence is corrected. The pilot's speed of response is too slow to correct the divergence and an automatic, or 'active', control system is essential.

The FBW system provides high-integrity automatic stabilisation of the aircraft to compensate for the loss of natural stability and thus enables a lighter aircraft with a better overall performance to be produced compared with a conventional design. It also provides the pilot with very good control and handling characteristics which are more or less constant over the whole flight envelope and under all loading conditions.

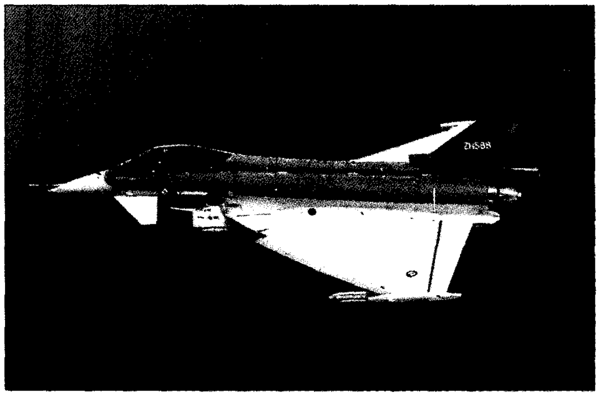


Fig. 1 Eurofighter Typhoon [photo: courtesy of British Aerospace Defence Ltd.]

Aircraft with FBW flight control systems first came into service in the late 1970s. The concepts are not new; in fact, all guided missiles use this type of control. What has taken the time has been the development of the failure survival technologies to enable a high-integrity system to

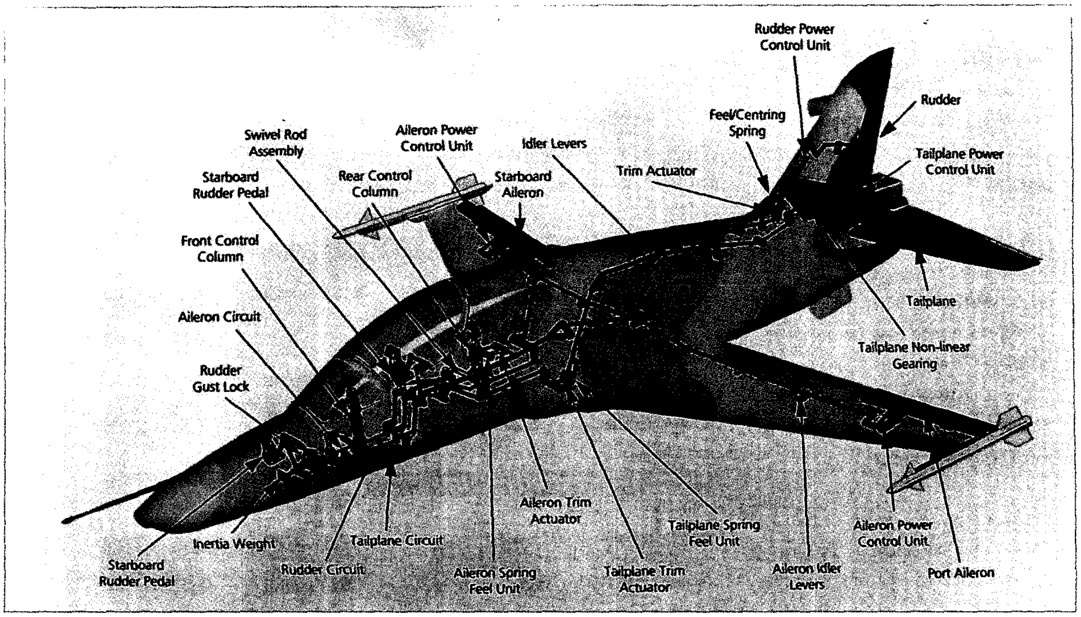


Fig. 2 Mechanically signalled flying control system in the British Aerospace Hawk [illustration: courtesy of British Aerospace Defence Ltd.]

be implemented economically with the required safety levels, reliability and availability. A major factor has been the development of failure survival digital flight control systems and their implementation in VLSI microcircuits. There are other technologies where development has been essential for FBW control, such as failure survival actuation systems to operate the control surfaces.

All new fighter designs exploit FBW control. Fig. 1 illustrates the Eurofighter Typhoon.

A recent development in military aircraft is the emergence of 'stealth' technology where the aircraft configuration and shape are specifically designed to reduce its radar cross-section. In general, the stealth features reduce the aircraft's natural stability and damping, and FBW control is essential to achieve good handling and control characteristics.

The new generation of civil airliners exploit FBW control. Examples are the Airbus Industrie A320, A330 and A340, and the Boeing 777.

Mechanically signalled flying controls

Before moving on to discuss FBW control in more detail, it is instructive to see how conventional mechanically signalled flying controls are implemented in an aircraft. Fig. 2 shows the mechanically signalled flying control system installed in the British Aerospace Hawk. The inevitable mechanical complexity of the control rods and linkages can be seen.

FBW basic concepts and elements

Fig. 3 shows the basic elements of a FBW flight control system. Note:

- The total elimination of all the complex mechanical control runs and linkages—all commands and signals are transmitted electrically along wires, hence the name fly-by-wire
- The interposition of a computer between the pilot's commands and the control surface actuators
- The aircraft motion sensors which feed back the components of the aircraft's angular and linear motion to the computer
- The air data sensors which supply height and airspeed information to the computer
- Not shown in the Figure is the redundancy incorporated to enable failures in the system to be survived.

The pilot thus controls the aircraft through the flight control computer, and the computer determines the control surface movement for the aircraft to respond in the best way to the pilot's commands and achieve a fast, well damped response throughout the flight envelope.

Electrical data transmission

Electrical transmission of signals and commands is a key element in a FBW system. Modern systems use a serial digital data transmission system with time division multiplexing. The signals can then be transmitted along a network or 'highway' comprising two wires only as only one set of data is being transmitted at any particular time. Fig. 4 shows how a digital flight control system is interconnected using a digital data bus.

Military FBW generally use the well established Mil. Std. 1553 databus system. The links and bus use a screened twisted pair of wires with connection to the bus

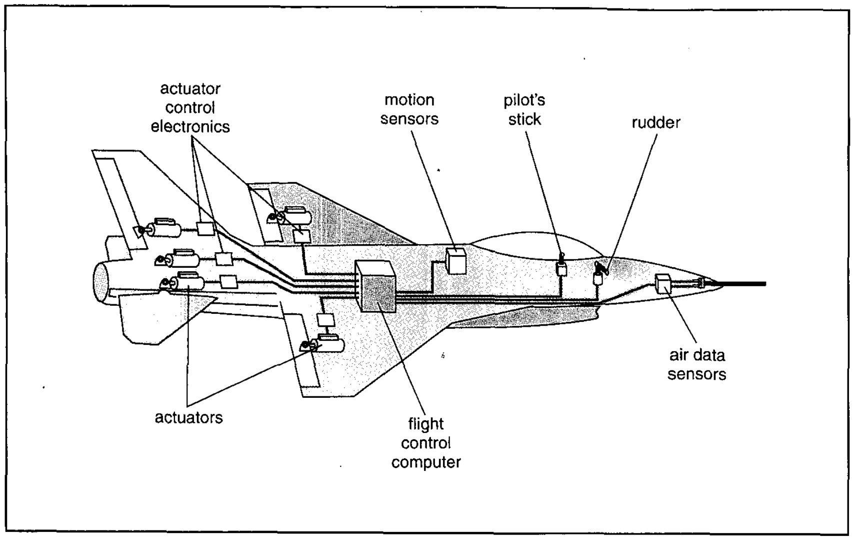


Fig. 3 Basic elements of a FBW flight control system

through isolating transformers. This is a command/response system with the bus controller function embedded in the flight control computers. It has a data rate of 1 Mbit/s and a word length of 20 bits to encode clock, data and address and so can receive or transmit up to 50 000 data words a second.

The Boeing 777 uses the new ARINC 629 databus system. This is an autonomous system and operates at 2 Mbit/s. The links and bus use an unscreened twisted pair of wires with connection to the bus through demountable current transformer couplers. The electronic complexity required in these systems to code the data and transmit it, or to receive data and decode it, is encapsulated in one or two integrated microcircuits.

FBW control surface actuation

The actuation systems which control the movements of the control surfaces are vital elements in a FBW system. They must be able to survive any two failures and carry on operating satisfactorily in order to meet the aircraft safety and integrity requirements (discussed later in the article). A typical quadruplex actuation system comprises four totally independent first-stage actuators which force-add their outputs to drive the power control

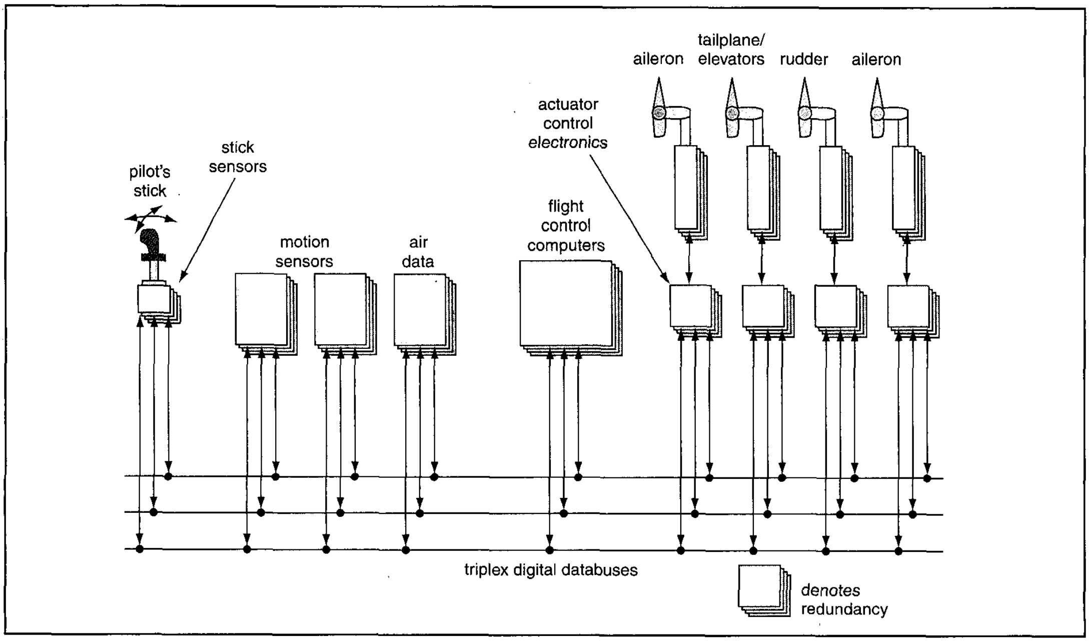


Fig. 4 Flight control system bus configuration

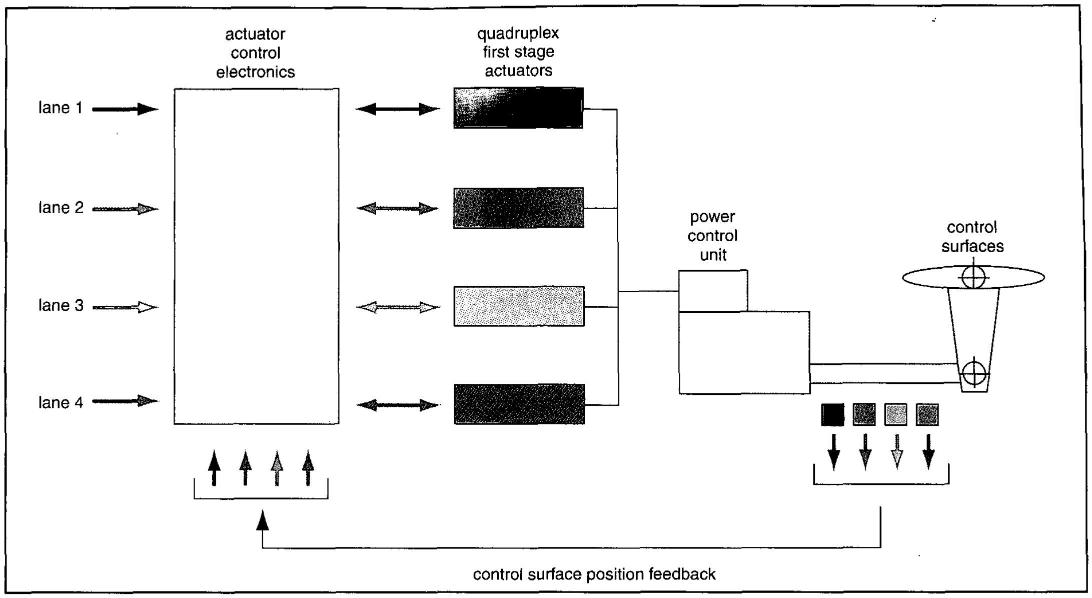


Fig. 5 Quadruplex actuation system

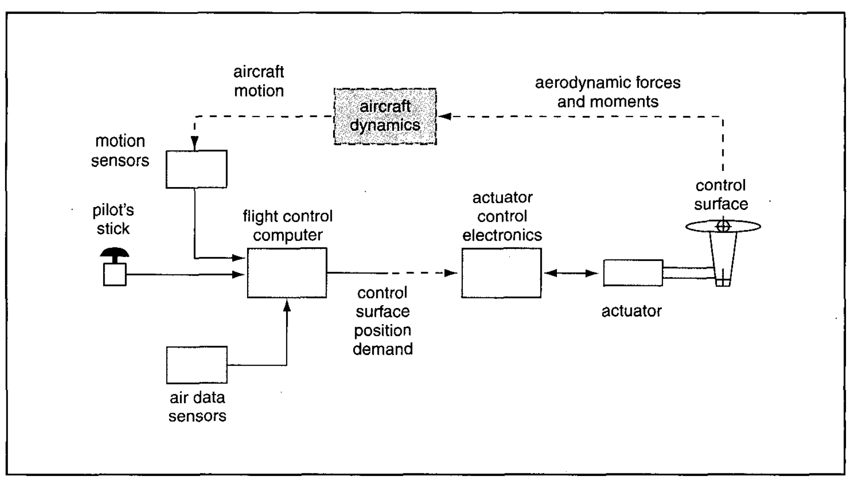
unit (PCU) servo control valve, and is shown schematically in Fig. 5.

There is no mechanical feedback from the PCU actuator to the servo control valve as there is in a conventional non-FBW system. Instead, the position of the control surface is fed back electrically to the input of the actuator control electronics; four independent position sensors are used to maintain the required integrity. The overall feedback improves the speed of response of the actuation system by a factor of about ten compared with a conventional PCU in a non-FBW system. Fast response is absolutely essential in a FBW actuation system in order to minimise the lags in the FBW loop. A typical agile fighter which is aerodynamically unstable would diverge exponentially, with the divergence doubling every 0·2 s in the absence of FBW control. The response of the FBW system to correct any divergence must thus be very fast.

The failure survival philosophy of a quadruplex actuation system is that if one actuator fails the three good ones can override it. The failed actuator is identified by comparing its control signals with the other three on the assumption that the probability of more than one failing at precisely the same instant is extremely remote. (All four actuators are totally independent in terms of separate power supplies, control electronics etc.) the failed actuator is then hydraulically bypassed leaving three good actuators in command.

A second subsequent actuator failure is detected by a similar process; two actuators are in agreement, one

Fig. 6 Fly-by-wire flight control system



differs, therefore it must be the failed one. The second failed actuator is then bypassed leaving the remaining two good actuators in control. In the extremely unlikely event of a subsequent third failure, the control surface would remain in the position at the time of failure with one good actuator opposing the failed one.

Motion sensor feedback

Fig. 6 illustrates the key features of FBW in simple diagrammatic form. A FBW system has to have motion sensor feedback by definition—without these sensors the system is classified as a 'direct electric link' system. The motion sensors comprise:

- Rate gyros which measure the angular rates of rotation of the aircraft about its pitch, roll and yaw axes.
- Linear accelerometers which measure the components of the aircraft's acceleration along these axes.

The feedback action of these sensors in automatically stabilising the aircraft can be seen from Fig. 6. Any change in the motion of the aircraft resulting from a disturbance of any sort (e.g. gust) is immediately sensed by the motion sensors and causes the computer to move the appropriate control surfaces so as to apply forces and moments to the aircraft to correct and suppress the deviation from the commanded flight path. An automatic 'hands-off' stability is achieved with the aircraft rock steady if the pilot lets go of the control stick. The motion sensors also enable a manoeuvre command control to be exercised by the pilot, as will be explained later. Because of their vital role and the need to be able to survive failures, they are typically at a quadruplex level of redundancy.

Air data

The need for air data information on the airspeed and height is to compensate for the very wide variation in the control surface effectiveness over the aircraft's flight envelope of height and speed combinations. For example, low speed at low altitude during take off and landing, high speeds approaching Mach 1 at low altitude in the case of a military strike aircraft, cruising subsonic flight at high altitude where the air is very thin, supersonic flight at medium to high altitude etc.

The variation in control surface effectiveness, or 'stick force per *g*' as it is referred to, can be as high as 40:1. For example, at 45 000 ft it may require 20° of tailplane deflection to produce a normal acceleration of 1*g*. (Normal means at right angles to the aircraft's flight path.) At very high subsonic speeds of around 600 knots at very low altitude, however, it may only need 0·5° deflection, and 20° would produce sufficient *g* to break up the aircraft. It is thus necessary to adjust or scale the control surface deflection according to the aircraft's airspeed and height.

The aircraft response and controllability are also dependent on its Mach number, that is the ratio of the true airspeed of the aircraft to the local speed of sound.

Fig. 7 Integrated air data transducer system [photo: courtesy of Marconi Avionics Ltd.]

The FBW system is thus supplied with airspeed, height and Mach number in order to adjust or scale the control surface deflections accordingly. (This process is referred to as 'air data gain scheduling' in the USA.) Totally independent, redundant sources of air data information are required in order to meet the safety and integrity requirements. Generally, quadruplex sources are used.

The FBW system also requires information on the aircraft incidence angles, that is the local flow angles in the pitch and yaw planes between the airstream and the fuselage datum.

The pitch incidence angle controls the wing lift and it is essential to monitor that the incidence angle is below the maximum value to ensure that a stall condition is not reached. (A stall results when the airflow starts to break away from the upper surface of the wing with consequent sudden loss of lift and control.) The incidence angle in the pitch plane (or angle of attack as it is often called) is used as a control term in the pitch FBW system. The incidence angle in the yaw plane is known as the angle of sideslip, and is used as a control term in the FBW rudder control system.

Fig. 7 illustrates an integrated air data sensor unit which combines the incidence vane and the Pitot-static probe; the vane aligns itself with the airstream in the same manner as a weather vane. The unit contains the total pressure and static pressure sensors together with the associated electronics including a microprocessor to carry out the air data computations. It provides height, calibrated airspeed, Mach number and local flow angle information to the FBW system. Four of these air data transducer systems as they are known are installed on the Eurofighter Typhoon to meet the failure survival and integrity requirements.

Aerodynamic stability

It is appropriate at this point briefly to explain the difference between an aerodynamically stable aircraft and an unstable one.

To achieve stability in the pitch plane it is essential that the aircraft's CG (centre of gravity) is ahead of the aerodynamic centre where the lift acts, as shown in Fig. 8(*a*). However, to trim or balance the aircraft at the right incidence for a particular airspeed, the tailplane lift force has to act in a *downward* direction in order to create a nose up moment about the CG which is equal and opposite to the nose down moment from the wing lift.

Fig. 8(*b*) shows an aerodynamically unstable aircraft. The aircraft CG is now behind the aerodynamic centre. The aircraft can be trimmed by the tailplane whose lift now contributes to the overall lift. However, the tailplane has to be moved continually to counteract the divergent effect of a gust increasing the incidence thereby increasing the wing lift. This would in turn increase the pitching moment about the CG causing the incidence to increase still further and a divergently unstable situation unless corrected.

Importance of low weight

The vital importance of weight in an aircraft has already been mentioned and will now be explained in more detail. In a nutshell, every pound of unnecessary weight is geared up by 10:1 in its effect on the aircraft's performance; so that 100 lb of unnecessary weight becomes the equivalent of 1000 lb in terms of its effect on the aircraft range and payload.

This is because unnecessary weight means a stronger and therefore heavier structure to withstand the maximum *g* force requirements. More lift is therefore required from the wings to support this additional weight and this means increasing the incidence. This increases the wing drag, which follows an approximate square law. Increased thrust is required from the engines to

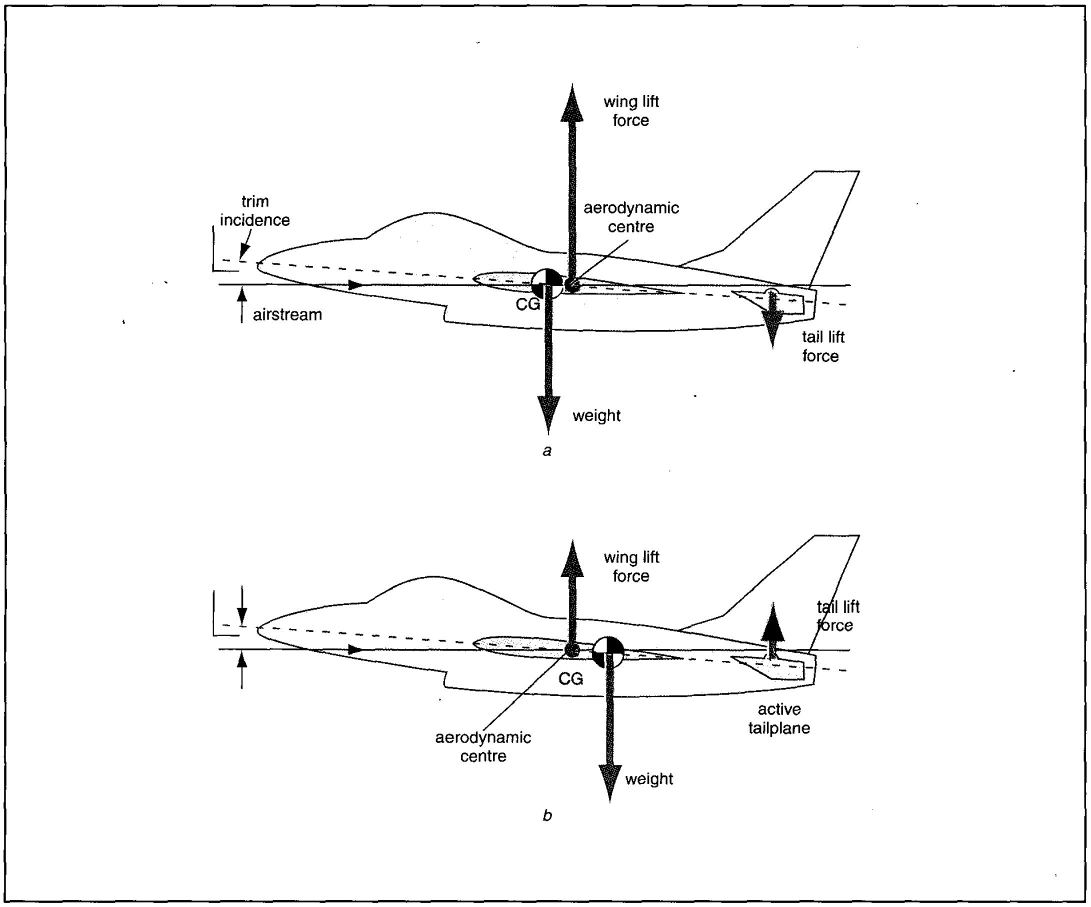
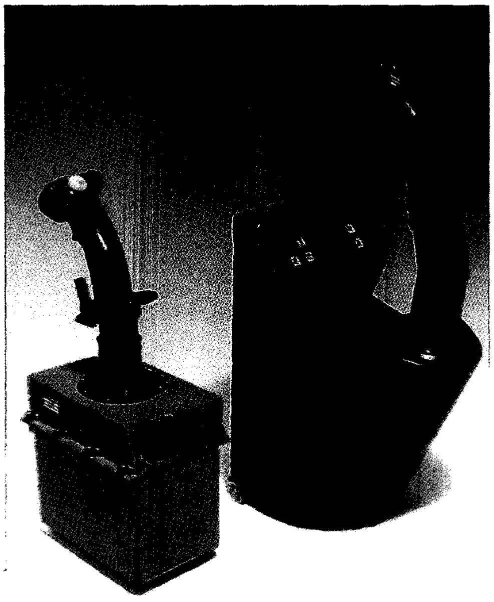


Fig. 8 Stable (*a*) and unstable (*b*) aircraft configurations



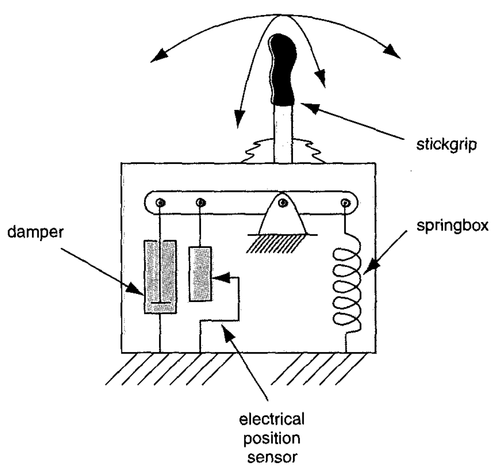


Fig. 9 Mini control sticks and, above, construction schematic

counteract this increase in drag and the fuel consumption is thus increased. So, for the same range the payload has to be reduced or, keeping the same payload means the range is reduced.

Advantages of FBW control

Increased performance

FBW enables a smaller tailplane, fin and rudder to be used, thereby reducing both aircraft weight and drag, active control of the tailplane and rudder making up for the reduction in natural stability.

For a civil airliner, reducing the stability margins and compensating for the reduction with a FBW system thus results in a lighter aircraft with a better performance and better operating economics and flexibility than a conventional design, for example, the ability to carry additional freight. Conventional airliners may have the space for additional freight containers, but the resulting rearward shift of the CG would give the aircraft unacceptably marginal handling characteristics. It should be noted that the carriage of containerised freight as well as passengers forms a very significant part of an airline's revenue.

For a military aircraft, such as an air superiority fighter, the FBW system enables aircraft configurations with negative stability to be used. These give more lift, as the trim lift is positive, so that a lighter, more agile fighter can be produced—agility being defined as the ability to change the direction of the aircraft's velocity vector. An increase in instantaneous turn rate of 35% is claimed for some of the new agile fighters.

Reduced weight

Electrically signalled controls are lighter than mechanically signalled controls. FBW eliminates the bulk and mechanical complexity of mechanically signalled controls with their disadvantages of friction, backlash (mechanical lost motion), structure flexure problems, periodic rigging and adjustment.

Mini control sticks

Give fingertip control and allow more flexibility in the cockpit layout—the displays are not obscured by a large control column, for example. The cockpit flight deck is very valuable 'real estate'.

Fig. 9 illustrates two mini control sticks. The illustration shows a centrally mounted control stick as installed in the Eurofighter Typhoon (right) and the side mounted control stick (left) as installed in the new Lockheed F22 'Raptor' fighter. The diagram shows the construction schematically.

The stick is a two-axis one, and provides pitch and roll

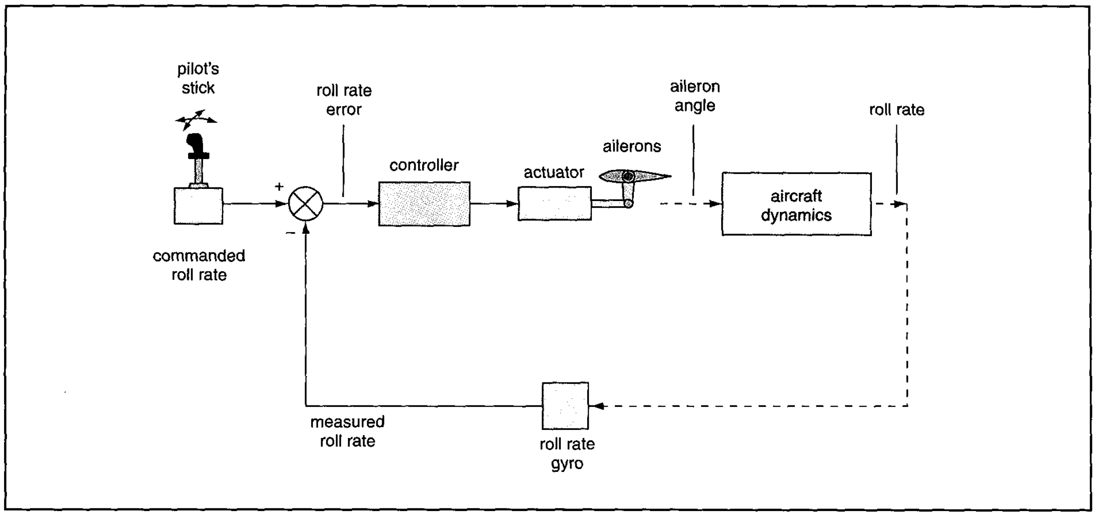


Fig. 10 Roll rate command system

electrical command signals. Typically, four independent electrical pick-offs are provided for each axis of control in order to meet the failure survival requirements. The damper provides a smooth feel to the stick movement.

A small breakout force is required to displace the stick from the central position in pitch and roll. Roll control is a simple linear spring characteristic. Pitch, however, requires a step increase in force at larger stick deflections and the spring rate is also increased so that larger forces have to be exerted when commanding high *g* manoeuvres. These characteristics are carefully tailored to meet the consensus of pilot approval and acceptance.

Hands-off stability

As explained earlier.

Carefree manoeuvring

The FBW computer continually monitors the aircraft's state to assess how close it is to its manoeuvre boundaries. It automatically limits the pilot's command inputs to ensure that the aircraft does not enter an unacceptable attitude or approach too near its limiting incidence angle (approaching the stall) or carry out manoeuvres which would exceed the structural limits of the aircraft.

A number of aircraft are lost each year due to flying too close to their manoeuvre limits and the very high workload in the event of a subsequent emergency. The FBW system can thus make a significant contribution to flight safety.

Manoeuvre command control

FBW can be used to give a closed-loop manoeuvre command control whereby the pilot commands a 'rate of pitch' or 'rate of roll' by moving the control stick. The flight control computer then automatically controls the movement of the control surfaces to manoeuvre the aircraft so that its pitch rate or roll rate is made to follow the pilot's command with little or no overshoot. The response is more or less constant over the height and speed envelope and range of load conditions, for example, carrying external 'stores'—a military euphemism for bombs, rockets, missiles etc. Carriage of external stores usually has a significant destabilising effect on the aircraft.

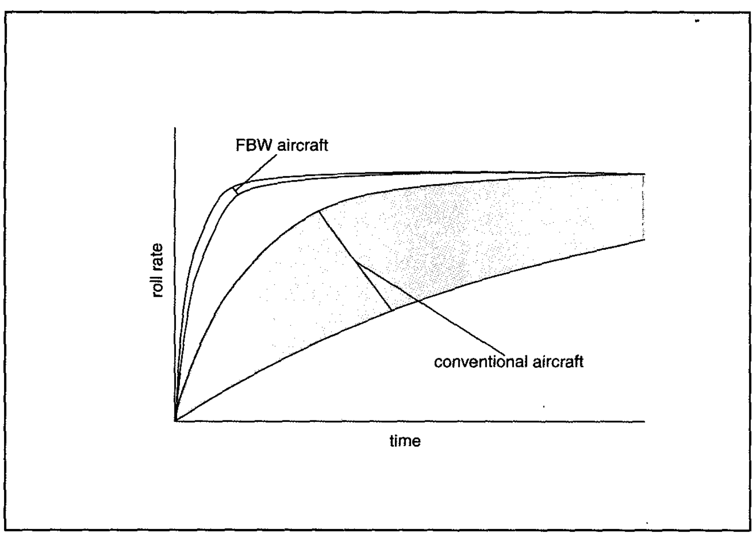


Fig. 11 Roll rate response

Fig. 10 is a block diagram of a closed-loop roll rate command system.

Consider what happens when the pilot pushes the stick to command a roll rate. At the instant the command is applied the roll rate is zero, so that the roll rate error produces a large aileron deflection. This creates a relatively large rolling movement on the aircraft so that the roll rate builds up rapidly. The roll rate error is rapidly reduced until the roll rate error is near zero, and the aircraft roll rate is effectively equal to the commanded roll rate. Because the roll rate creates an aerodynamic damping moment which opposes the rate of roll, the aileron deflection cannot be reduced to zero but is reduced to a value where the rolling moment produced is equal and opposite to the aerodynamic damping moment. The controller gain is sufficiently high, however, to keep the steady-state roll rate error to a small value. A much faster roll response can be obtained compared with a conventional open-loop system, as can be seen in Fig. 11; the variation in response across the flight envelope is also much less.

Aircraft need to bank to turn, so that a fast, precise roll response is required. Push the stick sideways and a roll rate directly proportional to the force exerted on the stick is obtained. Return the stick to the centre when the desired bank angle is reached and the aircraft stops rolling, without any overshoot.

Fig. 12 shows a FBW pitch rate command system. Consider now what happens when the pilot exerts a force on the stick to command a pitch rate. The aircraft pitch rate is initially zero so that the resultant pitch rate error causes the computer to demand an appropriate deflection of the tailplane from the trim position. The ensuing lift force acting on the tailplane exerts a pitching moment on the aircraft about its CG causing the pitch attitude to change and the wing incidence to increase. The resulting lift force from the wings provides the necessary force at right angles to the aircraft's velocity vector to change the direction of the aircraft's flight path so that the aircraft turns in the pitch plane. The increasing pitch rate is fed back to the computer reducing the tailplane angle until a condition is reached when the aircraft pitch rate is equal to the commanded pitch rate.

The pitch rate error is thus brought to near zero and maintained near zero by the automatic control loop.

To stabilise an aircraft with low or negative aerodynamic stability requires the tailplane (or foreplane and elevons in some aircraft configurations such as the Eurofighter Typhoon) to move as the incidence angle changes to develop an opposing pitching moment to prevent the incidence diverging. A control signal proportional to incidence as well as pitch rate is thus required to control the tailplane movement. This is frequently obtained by computing the change in pitch angle from the pitch rate gyro output, as the change in pitch angle is directly related to the change in incidence.

The advantage of integrating the pitch rate gyro output to obtain a quasi-incidence term is that it avoids an additional sensor as pitch rate is essential, anyway, as a control term. Rate gyros are very rugged and reliable devices and so provide a 'core stabiliser system' which is sufficient to stabilise the aircraft. A blend of control terms

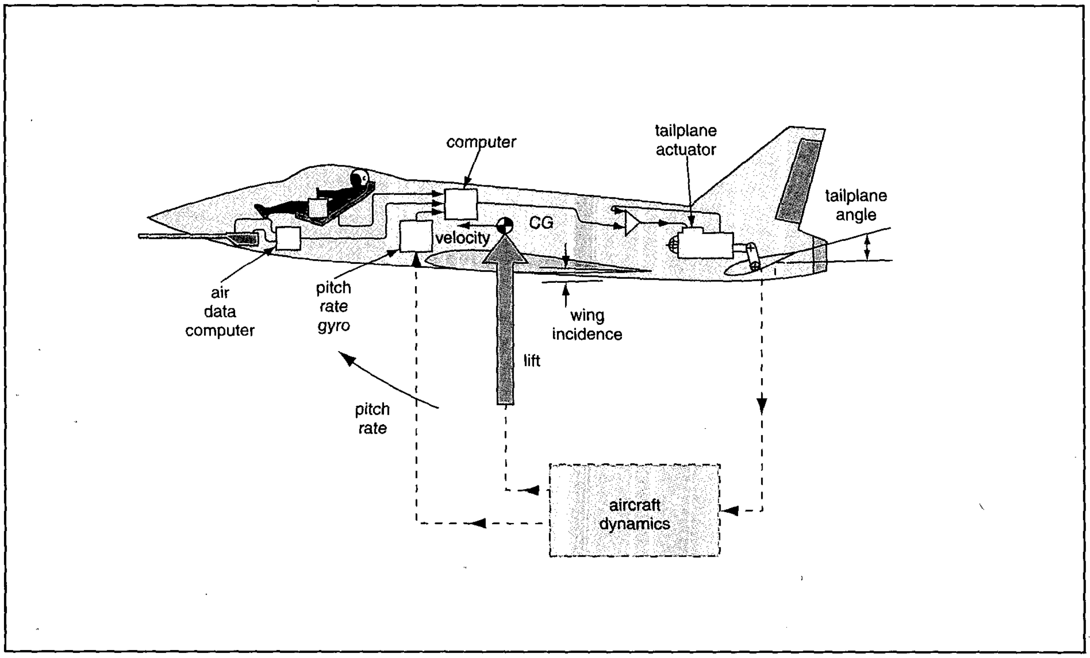
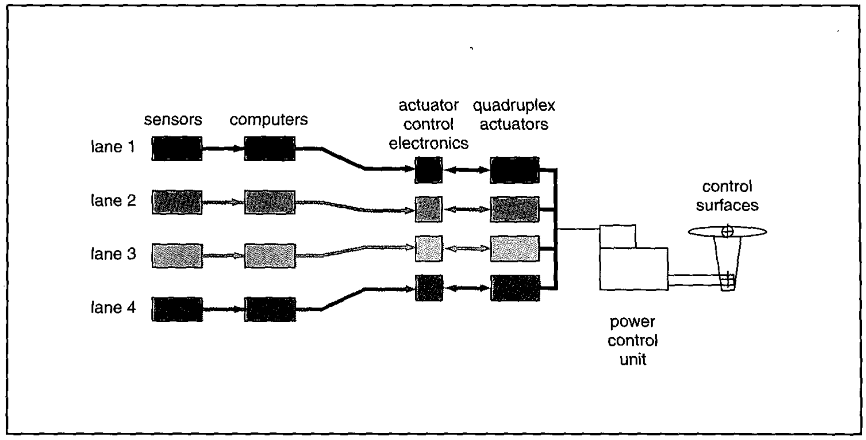


Fig. 12 Pitch rate command FBW loop

Fig. 13 Quadruplex system



is generally used; however, to obtain the optimum response at high angles of incidence or high *g*, incidence and normal acceleration control terms are incorporated into the control law.

Pitch rate command enables precise 'fingertip' control to be achieved. For example, to change the pitch attitude to climb, gentle pressure back on the stick produces a pitch rate of a few degrees per second; let the stick go back to the central position and the pitch rate stops in less than a second with negligible overshoot with the aircraft at the desired attitude. Increasing the stick force produces a proportionate increase in pitch rate.

The normal acceleration, or *g*, is equal to the aircraft velocity multiplied by the pitch rate, so that for a given speed the *g* is directly proportional to the rate of pitch.

It should be noted that notch filters are incorporated in the FBW control loops to attenuate the loop gain at the structural resonance frequencies so that these resonances are not excited.

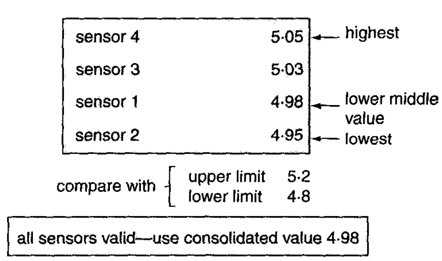


Fig. 14 Example of voting and consolidation process

Ability to integrate additional controls

These controls need to be integrated automatically to avoid an excessive pilot workload—too many things to do at once:

- Leading and trailing edge flaps for manoeuvring and not just for take-off and landing.
- Variable wing sweep.
- Thrust vectoring.

Ease of integration of the autopilot

The fast response achieved with pitch rate and roll rate manoeuvre command greatly assists the integration of the autopilot where a demanding autopilot performance is required and the excursions from the desired flight must be kept small: for example, automatic terrain following at 100–200 ft above the ground at over 600 knots—or fully automatic landing in zero visibility conditions.

Failure survival

A FBW system must have the same level of safety and integrity as the simple mechanical linkage system it replaces. Safety is specified in terms of the probability of a failure occurring in the FBW system which would result in catastrophic consequences to the aircraft. For a military aircraft the probability of a catastrophic failure in the FBW system must be less than *1 in 10^7 per hour of flight*. For a civil aircraft the probability must be less than *1 in 10^9 per hour of flight*.

These integrity requirements can only be met by designing the system so that it has sufficient redundancy to survive any two successive failures and carry on working satisfactorily. A sufficient number of totally independent electrical and hydraulic supplies must be provided—typically three to four.

Quadruplex redundancy is frequently used in military aircraft to achieve the required safety and integrity. Civil aircraft, however, have a higher level of redundancy, as will be explained. Fig. 13 shows a basic quadruplex system with four independent sensor and computing lanes controlling a quadruplex actuator system. Because the four lanes are totally independent the chance of two failing simultaneously is very remote. A single failure in a lane can be overridden by the three good lanes. To survive a second failure, however, it is necessary to detect the failed lane and disconnect it.

Failures are detected by cross-comparison of the lanes and majority voting on the 'odd man out' principle. The output of each sensor in a set measuring a particular quantity is first compared with the others to check that the output is valid. The four outputs are then consolidated into a single value so that all four computers use the same data in their computation of the required control surface angles. There are a very large number of practical voting and consolidation algorithms. A simple one which is widely used is to select the lower of the middle two values and compare the highest and lowest values with the lower middle value.

An example of the process is shown in Fig. 14. The hypothetical values are from four identical sensors measuring the same quantity at a particular instant in time. (Sensors are typically sampled 100 times a second.)

The disconnect tolerance is a compromise between avoiding nuisance trip-outs when a sensor is on the edge of its tolerance accuracy and the disconnect transient experienced by the aircraft when a failed sensor is disconnected and the consolidated value changes to a new value (the middle of the three remaining sensor outputs).

The electronics are designed to withstand very high levels of EMI and use very sophisticated screening techniques

It should be noted that the computer iteration periods are generally synchronised through the computer software to avoid data staleness problems.

The tasks carried out by each lane of the quadruplex system are shown in Fig. 15.

Dissimilar redundancy

The failure survival philosophy discussed so far has been based on the premise that the probability of all four lanes failing at the same instant in time is so small that it can be treated as negligible. However, there are circumstances which could affect all four lanes simultaneously and result in a common failure. Simultaneous failures which can result in such circumstances are known as 'common-mode' failures. Possible causes of common-mode failure are:

- electromagnetic interference (EMI) —for example over-flying a powerful radio or radar transmitter
- fire
- lightning strikes: very large electromagnetic pulses with electric field strengths of hundreds of volts per metre can be produced and a very wide spectrum of electromagnetic radiation frequencies generated
- battle damage in the case of a military aircraft
- incorrect maintenance
- common design errors, e.g. software errors.

Every care is taken to minimise these risks. The electronics are specially designed to withstand very high levels of EMI and use very sophisticated screening

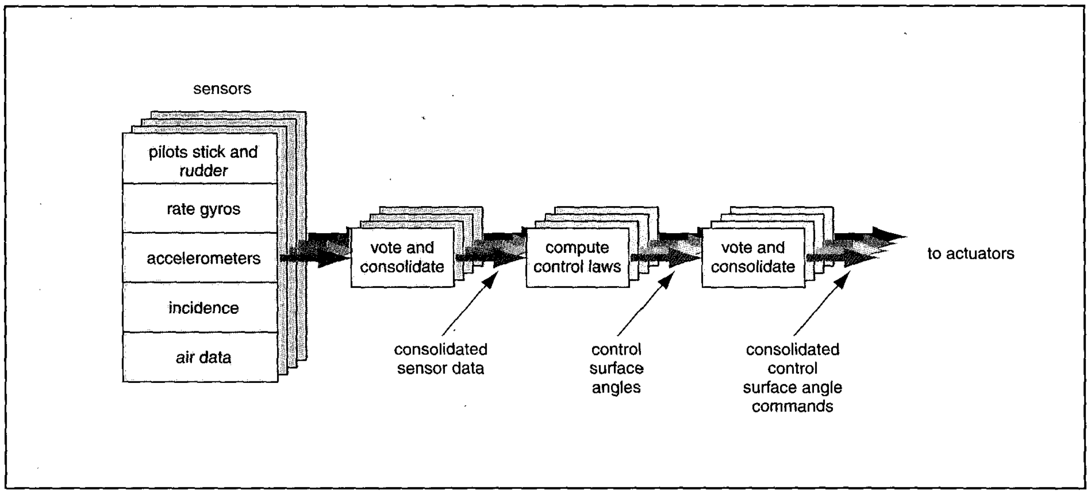


Fig. 15 Lane processing tasks

Fig. 16 Boeing 777 primary flight computer [photo: courtesy of Marconi Avionics Ltd.]

techniques. Earlier analogue flight control systems have experienced malfunctions when overflying radio/radar transmitters—the new generation digital systems are very much more robust, and can meet the very stringent EMC requirements.

The effects of fire or battle damage are minimised by physical separation of the different lanes and a 'brick wall' type construction in the individual electronic units with physical barriers separating the lanes in the units.

The risks of incorrect maintenance are minimised by adopting very stringent procedures and practices, and constant monitoring to ensure these are being followed.

Lastly, the problem of common design errors, particularly software errors, is a major one. It is also very difficult, if not next to impossible, to prove that there are no software errors present. Very stringent procedures are used in generating and testing the software to minimise the risk of errors.

The civil authorities require the use of dissimilar systems in the redundancy provided in the flight control system, because of the difficulty or impossibility of excluding the risk of a common error being present in a redundant system comprising similar elements.

Different sensors and computers controlling different control surfaces are used to achieve dissimilar redundancy. Different microprocessors obtained from different manufacturers are used to avoid the risk of common hardware faults.

The same software tasks are given to two different software groups, each program being written for a different manufacturer's microprocessor to avoid common errors. A reversionary analogue system is sometimes installed to provide a 'get you home' capability in the very unlikely event of complete loss of the primary system.

Mechanical operation of controls such as the tailplane trim and rudder provides a further back-up mode.

Fig. 16 shows one of the primary flight computers (PFC) which are installed in the Boeing 777 airliner. Each PFC comprises a channel, and there are three separate PFCs providing three independent channels in the primary flight control system. The PFC contains three independent dissimilar processors which are physically segregated within the box, the software for the three processors being generated by independent groups to the same requirement specification. The system normally operates with one processor in each PFC in command, with the other two acting as monitors and is able to absorb multiple random component failures or a combination of a software generic error and random failures.

Conclusions

This article has provided an overview of FBW control and the key areas involved. A particular aim has been to show the wide range of engineering disciplines required for FBW systems.

Further reading

BRIÈRE. D., FAVRE, C., and TRAVERSE, P.: 'A family of fault tolerant systems: electrical flight controls, from Airbus A320/330/340 to future military transport aircraft', ERA Avionics Conference, 1993

COLLINSON, R. P. G.: 'Introduction to avionics' (Chapman & Hall, ISBN 0 41248 250 9)

Interim Defence Standard DEF STAn 00-55: 'The procurement of safety critical software in defence equipment', 5th April 1991

McLEAN, D.: 'Automatic flight control systems' (Prentice Hall)

MIRZA, N. A.: 'Primary flight computers for the Boeing 707' ERA Avionics Conference, 1992, ERA Report 92-0809

RTCA-EUROCAE DO178B/ED-12B: 'Software considerations in airborne systems and equipment certification', December 1992

RUSHBY, J.: 'Formal methods and the certification of critical systems', Technical Report CSL-93-7, December 1993, Computer Science Laboratory, SRI International

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