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European Commercial Aircraft before the Airbus A320

1.1. Introduction

European industry abounds in examples that highlight the 4 major stages of the evolution of commercial aircraft actuation:

– the Caravelle (Sud Aviation), the first short/medium-range jetliner that used, from the end of the 1950s, irreversible servocontrols without the possibility for human-powered control[1] of the 3 axes of primary flight controls (roll, pitch and yaw);

– the Concorde (Sud Aviation and British Aircraft Corporation), the only supersonic commercial jetliner, which by the mid-1970s introduced electrically-signaled flight controls driven by analog electric controllers;

– the Airbus A320 that introduced by the mid-1980s electrically-signaled flight controls with digital computers, which are often called *Fly-by-Wire* (FbW);

– the Airbus A380 that by the mid-2000s introduced electrically-powered actuators and electrically-powered local hydraulic power generation used as backup.

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1 The Caravelle used some equipment, concepts and operating experience feedback provided by the Comet (De Havilland), the first commercial jetliner put in service 7 years earlier and whose first versions had a difficult career start.

This chapter focuses only on the first 2 examples, the Airbus A320 and A380 being dealt with in their own specific chapters.

1.2. The Caravelle and irreversible primary flight servocontrols

At the end of the 1930s, several planes were already using hydraulic actuators for end-stop to end-stop positioning functions (extension/retraction of landing gear, deployment/retraction of wing flaps, opening/closure of engine cowling flaps) or functions of force transmission for wheel braking (see Figure 1.7 in Volume 1 [MAR 16b]). For primary flight controls, hydraulic actuators were also installed, along with cable controls that transmitted pilot actions to mobile surfaces. This allowed for the imposition of the flight control surface position setpoints by the automatic pilot when this was engaged (see Figure 1.8 of Volume 1 [MAR 16b]). Due to the increase in aircraft size, speed and flight duration, the need to reduce the level of force generated by the pilot for primary flight controls rapidly became essential. The introduction of *tabs*, deflected in the direction opposite to that intended for flight control surface deflection, provided assistance to the pilot's efforts without using an airborne power source: being subjected to aerodynamic forces, the tab produces a deflection moment that orients the flight control surface in the intended direction of movement. The application of this concept has led to several variants [LAL 02, ROS 00]:

– the *servo tab* (Figure 1.1(a)), for which the pilot acts only on the tab (if the assistance is insufficient, the bell crank arrives at end-stop and then the pilot acts directly on the flight control surface);

– the *auto tab* (Figure 1.1(b)), for which the pilot acts only on the flight control surface (tab deflection results from the flight control surface movement relative to the fixed surface);

– the *spring tab* (Figure 1.1(c)), for which the tab generates assistance only beyond a certain value of the maneuvering force, which allows for the improvement of control accuracy at small deflections;

– the *servo tab with compensation panel* (Figure 1.1(d)), which increases the servo tab aid rate due to the moment produced by a panel subjected to the difference in pressure between the lower surface and the upper surface of the wing profile.

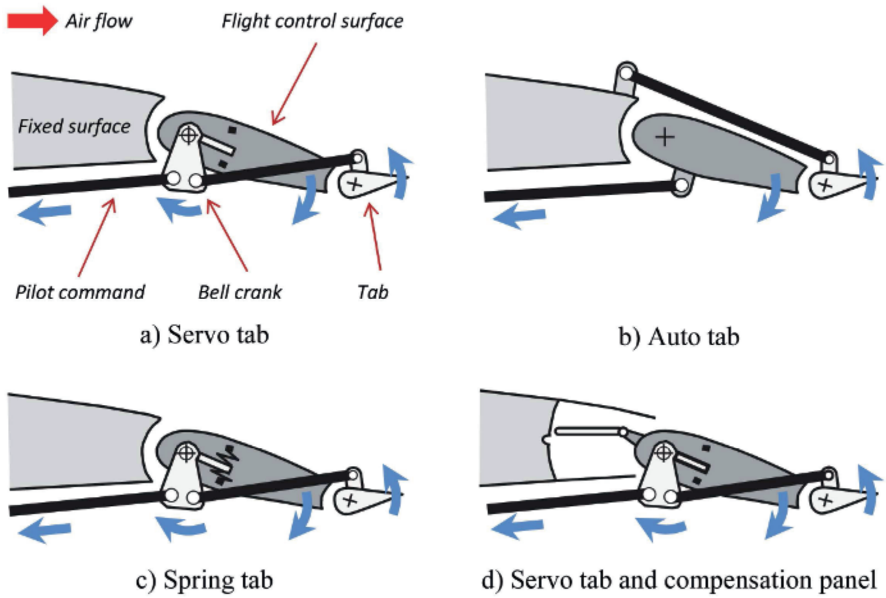

Figure 1.1. *Aerodynamic assistance concepts. For a color version of this figure, see www.iste.co.uk/mare/aerospace3.zip*

This form of assistance, still used today on low-capacity and low-cruising-speed aircraft, has the advantage of simplicity, as the assistance is generated by aerodynamic forces. On the contrary, its field of application and interest are limited by several drawbacks. The assistance rate strongly depends on the speed relative to the air, flight control surface deflection and aircraft behavior. Consequently, it is ill-suited to large aircraft and high speed. Its setup, which necessarily involves kinematic modifications after flight tests, is lengthy and tedious.

A further solution involves the insertion of a hydraulic actuator in series with the mobile surfaces mechanical actuation chain. The irreversible Jacottey-Leduc servocontrol, presented in Figure 1.10 of Volume 1 [MAR 16b], was, for example, fitted in line with a control linkage on the Armagnac commercial aircraft (SNCASE SE-2010) that made its first flight in 1949 and was commissioned in 1952. The level of forces to be generated was such that it allowed for manually resuming its control in case of failure of servocontrol, whose output ram was then functionally connected with the input ram.

The Caravelle (Sud Aviation SE-210) (Figure 1.2), which made its first flight on 27 May 1955 and was commissioned in April 1959, eliminated the need for manual control in case of servocontrol failure. For this purpose, this type of aircraft, of which 282 units were manufactured by 1973 and which was in use until 2005, featured 4 irreversible and redundant hydromechanical servocontrol systems, called *Servodynes*, for the 3 primary flight control axes (left aileron and right aileron, elevator, rudder control surfaces). The widely redundant architecture of hydraulic power generation and distribution has been consequently designed, taking into account the critical functions to be developed [FLI 55]. It is also worth noting that the commercial exploitation of the Caravelle has contributed to the development of maintenance practices that were fit for high-criticality hydraulic systems [DAR 65].

Figure 1.2. *SE-210 Caravelle (© Air France Archives)*

1.2.1. *Servodyne servocontrol*

A Servodyne servocontrol (Lockheed) (Figure 1.3) replicates at the level of the driven load the position requested by the pilot, independently of the forces to be overcome in order to generate movement. It locally achieves linear position closed-loop control, which is hydraulically powered and features mechanical entry of position setpoint.

Figure 1.3. *The Caravelle Servodyne under maintenance at Arlanda Airport (© SAS Scandinavian Airlines)*

In order to meet reliability requirements, each Caravelle servocontrol system is a redundant physical unit with tandem architecture (2 pistons with the same revolution axis) with force summing, operating in active/active mode (see Volume 1, Chapter 2 [MAR 16b]). The Caravelle Servodyne (Figures 1.4 and 1.5) features 2 actuators operating in parallel from a mechanical point of view: although the drawing shows them as connected in series, back-to-back, the rods of the 2 actuators are connected to the support structure and the 2 half-bodies of each actuator are connected to one another and with the driven load. The load paths for the transmission of commands to the input lever and the transmission of efforts to the driven load are divided in half. Thus, the actuation function implements 2 parallel power channels, from the actuator support structure to the driven load. To provide independence of the 2 channels from crack propagation, the servocontrol system has 2 half-bodies, each of which is associated with its power channel. The failure response of one of the channels is of the *fail-safe/fail-passive* type: in principle, the defective channel offers no resistance to the movement imposed by the remaining operational channel.

The Caravelle Servodyne servocontrols develop a maximal force of 27,600 daN under a supply pressure of 172 bar when the 2 bodies are active. Their stroke is 120 mm for the ailerons and 150 mm for the elevators. As shown in Figures 1.4 and 1.5, each of these 2 back-to-back actuators has a (half) differential actuator with moving body ❶, a *preferential valve assembly* ❷, a *distributor valve* ❸ and a *jam warning transmitter* ❹. The 2 channels are identical and symmetrical. Given its relative simplicity, this servocontrol system is a good example for the subsequent illustration of the architecture analysis and identification of generic functions such as those presented in Chapter 1 of Volume 1 [MAR 16b][2]. Several elements that may be used to identify the technologies employed to develop these functions are also provided.

1.2.1.1. *Power supply*

A preferential valve assembly associated with the actuator rod allows the actuator to be supplied at a pressure ranging between 148 and 182 bar from one of the 2 (normal or backup) hydraulic power networks. The concept of moving-body and fixed-rod actuator facilitates the use of rigid piping for this block's supply, therefore avoiding the presence of high-pressure flexible pipes, which are far less reliable.

1.2.1.2. *Power transformation*

A differential actuator transforms hydraulic power into translational mechanical power. The rod is anchored to the supporting frame and the body is connected to the driven load. The hydrostatic sections on one side and the other of the piston are in a ratio of 2. By permanently applying supply pressure to the annular chamber (rod side), an identical load capacity is obtained in extension and retraction, depending on whether the other chamber is subjected to supply pressure or return pressure (which is negligible compared to supply pressure).

1.2.1.3. *Power metering*

A differential actuator allows for the metering of the transmitted power using only 2 variable resistors that form a divider bridge. This is done by a 2-way valve with 3 orifices, continuously and mechanically controlled. The variable hydraulic resistance function is implemented in the form of a sliding valve by a translating cylindrical spool. The control lever performs the comparator function of the closed-loop position control by subtracting the servocontrol body position from the spool position imposed by the pilot: the valve opening is indeed proportional to the position error between the pilot setpoint and the servocontrol body position (see Figure 1.5(a) of Volume 2 [MAR 17]).

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2 As mentioned in this chapter, the following lines confirm that the design is rendered more complex essentially by the conditioning and power management functions, to a far greater extent than closed-loop position control-associated functions.

1.2.1.4. *Fluid conditioning*

a) Filtering: each servocontrol channel has 5 integral filters: one on each supply channel, one on the rod-side chamber supply, one on the valve pressure supply (performed from this chamber) and one on the control line of the large section chamber.

b) Warming up: certain servocontrols are warmed up to a minimal temperature of 20°C using air coming from the engines. This allows for the maintenance of the performance level of the position control, particularly in terms of sensitivity and accuracy during high-altitude cruising.

1.2.1.5. *Power management*

a) Damping: a *dash-pot* associated with the slide valve improves the stability of position control in regard to disturbances resulting from the forces exerted by the driven load on the moving body.

b) Ensuring irreversibility: the check valve of the supply block avoids reverse flows from the low-pressure line to the piston chamber.

c) Selecting the available power source: the shuttle valve of the supply assembly block automatically selects the available power source and isolates the other source.

d) Protecting against overstress and overpressure: if the flight control surface is subjected to excessive aerodynamic load in the direction of the actuator extension, the pressure in the annular chamber increases and gives rise to a flow to the active pressure source accumulator. If the excessive load tends to cause retraction of the actuator, then the check valve inside the actuator rod acts as a pressure relief valve and allows a flow toward the annular chamber and the supply line.

e) Ensuring passive mode in case of failure: redundancy is provided by summing the forces developed by each of the channels on the servocontrol body. When 1 channel is defective, it must be hydraulically declutched from the load. If the fault is caused by the absence of pressure on its 2 supply networks (pressure below 35/48 bar), the channel is depressurized by automatic bypass of the preferential valve (supply block) assembly. If the fault is caused by slide valve jamming, the threshold springbox of the jam warning transmitter allows the disconnection of the lever from the jammed valve and the setpoint position can be applied to the other valve (see Volume 2, section 1.2.1 [MAR 17]). In this case, the pilot perceives an increased control load due to the threshold box calibration. The pilot is also informed about the jamming due to the contact established by the microswitch of the warning transmitter, which can then order the depressurization of the defective channel.

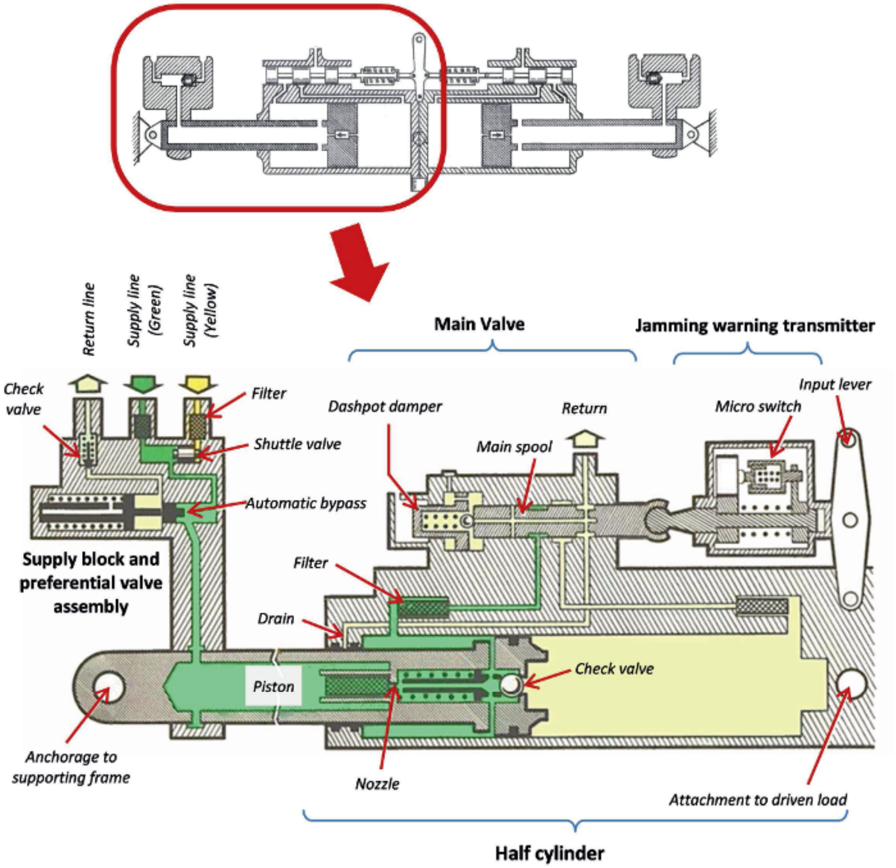


Figure 1.4. *Caravelle Servodyne servocontrol (according to [SAB 61, SWI 60]). For a color version of this figure, see www.iste.co.uk/mare/aerospace3.zip*

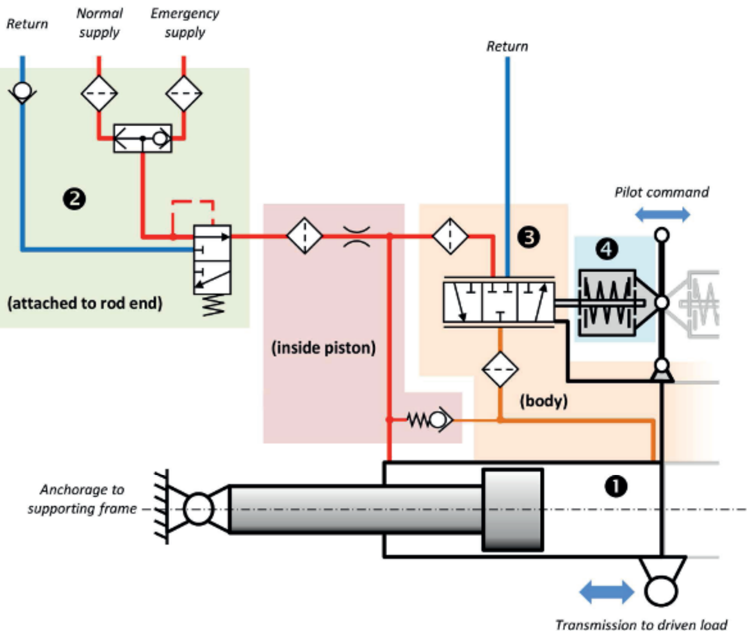


Figure 1.5. *Equivalent diagram of the Servodyne servocontrol (half-actuator, active normal mode). For a color version of this figure, see www.iste.co.uk/mare/aerospace3.zip*

1.2.2. *Artificial feel of load*

On the Caravelle, information was transmitted from the flight deck to servocontrols by cables and connecting rods, a common mechanical solution for that time period. Until then, the assisting actuators used for flight control simply amplified the force generated by the pilot. By means of their contribution to the actuation load, the pilot was therefore able to perceive the magnitude of the stresses he subjected the plane to, through the intermediary of mobile surfaces. The Servodynes on Caravelle are irreversible, which strongly improves flight control performances. On the contrary, due to this irreversibility, the effort required for input lever maneuvering (typically of 5 N) is rendered independent from the force applied to the driven load. Therefore, the pilot is deprived of any perception of mechanical stresses imposed on the aircraft structure by flight controls. The first versions of the

Comet (De Havilland) revealed the danger presented by this lack of perception of stresses. They showed that while the introduction of irreversible servocontrols was a significant progress in terms of performances, it had created a new need: the pilot had to artificially regain the feel of load. During its development, the Caravelle therefore directly benefited from this experience by integrating the solutions implemented on the most recent versions of the Comet.

The lever control system on Servodynes relying on pilot actions is schematically presented in Figure 1.6.

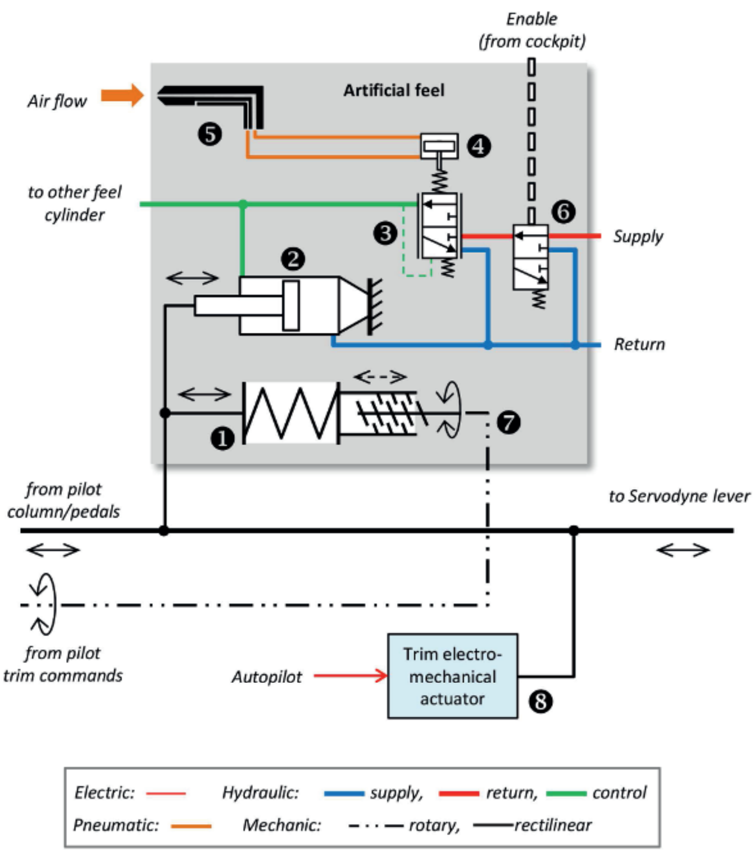


Figure 1.6. *Artificial feel on Caravelle flight controls. For a color version of this figure, see www.iste.co.uk/mare/aerospace3.zip*

A spring-based ❶ simple passive system featuring a torsion bar is connected in parallel with the transmission of mechanical orders. A maneuvering load that depends on the required control surface angle is consequently restored to the pilot. However, this device is not realistic in terms of the effect of aircraft speed relative to the air, which has a strong impact on the aerodynamic forces exerted on yaw and pitch control surfaces. The *Honson 159* active system allows the modulation of the pilot load in the speed range of 300–685 km/h (162–370 kt) in order to replicate this effect (*q-feel*). For each of the pitch and yaw axes, a single rod hydraulic actuator ❷ is added in parallel with the torsion bar. The pressure in the actuator active chamber is elaborated by a shared pressure-reducing valve ❸ whose setting is variable. This setting is modified by a pneumatic diaphragm actuator ❹ whose equilibrium is determined by the aircraft speed relative to the air. This speed information is provided by a Pitot tube ❺ that measures dynamic pressure as the difference between the total pressure and the static pressure of the air. The pilot can deactivate the q-feel by acting on the selector valve ❻.

Figure 1.6 also shows:

– The static equilibrium (trim) of flight controls. This allows the pilot to act on the neutral of commands by modifying the spring setting ❶ through mechanical transmission of trim commands ❼ from the flight deck. It is interesting to note that the trim command can be used as a backup channel for aircraft manual control in case of breakage of the normal transmission channel. Accompanied by routing and specific elements, it provides segregation and dissimilarity of the channels for command transmission from the pilot to servocontrols;

– Automatic pilot action. This imposes the position of control commands by means of an electromechanical actuator ❽, which is connected in parallel with the kinematic chain. This actuator has a torque limiter that allows the pilot to override the action of the automatic pilot, if needed.

1.2.3. *Hydraulic power generation*

The suppression of human-powered actuation possibility introduces a second induced effect: the criticality of servocontrol supply, whose loss becomes a catastrophic event. In order to guarantee hydraulic power supply availability, on the Caravelle, as well as on the Comet, 4 hydraulic networks have been implemented, known under the labels green, blue, yellow and red, as follows:

– the green main hydraulic circuit, which supplies all users, including a channel for each Servodyne;

– the blue main hydraulic circuit, which exclusively supplies the second channel of each Servodyne and the artificial feel system;

– the yellow emergency hydraulic circuit that takes over from the green or blue circuit by using their reservoir;

– the red emergency hydraulic circuit that is autonomous and supplies the parking brake and, in case of emergency, the landing gear extension, the brakes and the wing flaps. It has its own reservoir, which is not directly pressurized, but is located in a pressurized area.

The hydraulic power architecture (Figure 1.7) has parallel distribution (with flow share) and a permanent pressure source. The mineral fluid employed, containing additives, corresponds to the AIR3520 French standard (or FHS for *Fluide Hydraulique Standard*), which is the equivalent of the MIL-H-5606 American standard. The working temperature ranges between −54 and 130°C, with kinematic viscosity ranging between 2,500 and 3.5 cSt for these extreme temperatures. The auto-ignition temperature is 230°C. On the Caravelle, the operating pressure ranges between 148 and 182 bar in normal mode. Hydraulic power is generated by fixed displacement pumps with on/off functions that control fluid delivery to hydraulic power networks (see section 2.5):

– For the green and blue circuits whose pumps are permanently driven by aircraft engines, the on/off control is performed in the hydraulic domain through unloading valves. As long as the network pressure is too low, they connect the pressure delivery line of the pump to the high-pressure line of the network. When the pressure reaches the maximum level, the pump output is isolated from the high-pressure line and connected to the low-pressure line disconnect. The pump runs without hydraulic load and its power consumption is null (functionally speaking). Circuit pressure is held by oleo-pneumatic accumulators;

– For the yellow and red circuits that use electropumps, the on/off operation is controlled by pressure switches that enable the powering on or off of electropumps.

The power generation systems for the green and blue hydraulic circuits are similar. They each have their own reservoir (53 and 22 l), pressurized to relative 1.2 bar by the air coming from the engines. Each generation system implements 2 simultaneously active channels, each featuring an electrically controlled fire shut-off valve, an external gear pump (28 l/min for the green circuit and 14 l/min for the blue circuit)[3] and a high-pressure filter. The pumps are equipped with a mechanical fusible link that isolates the pump from its mechanical drive in case it stalls. The common output of the 2 channels is connected to 2 unloading valves mounted in parallel and whose setting is interlaced: connect at 148 bar and disconnect at 182 bar for the normal channel, connect at 176 bar and disconnect at 210 bar for the backup channel. Piston-type accumulators contribute to maintaining quasi-constant pressure in the circuit. If needed, the pilot can cut off the supply of servocontrols and of load feel devices by acting on mechanically signaled selector valves (on/off for the yaw and pitch load feel, green and blue/green only/blue only for the supply of 4 servocontrols).

Power generation of the yellow circuit is inactive in normal mode. It is activated by the pilot in case of failure of one of the 2 main circuits (green and blue). Battery autonomy (40 AH under 112 V) allows the electropump to function for 30 min, and the hydraulic accumulators, once charged, authorize 10 full deflections of the flight control surfaces. If the 2 engines fail, there is enough autonomy to supply flight controls and to land as soon as possible. At cockpit, the lever for the yellow generation activation has 3 simultaneous functions:

– it closes a contact that validates the electrical supply of the electropump by the batteries, depending on the contacts established by 2 pressure switches that electrically implement a duplex function of connect (117 bar)–disconnect (172 bar);

– it mechanically controls a hydraulic intake selector that establishes the connection with the green or blue reservoir to be used for the pump intake;

– it mechanically controls a second hydraulic selector valve that connects the pump delivery port to the high-pressure line to be supplied.

The circuit selector valve of the Servodyne supply assembly block automatically enables the yellow backup supply if the normal hydraulic circuit (green or blue) is depressurized.

3 The pumps of blue, yellow and red circuits are identical and interchangeable.

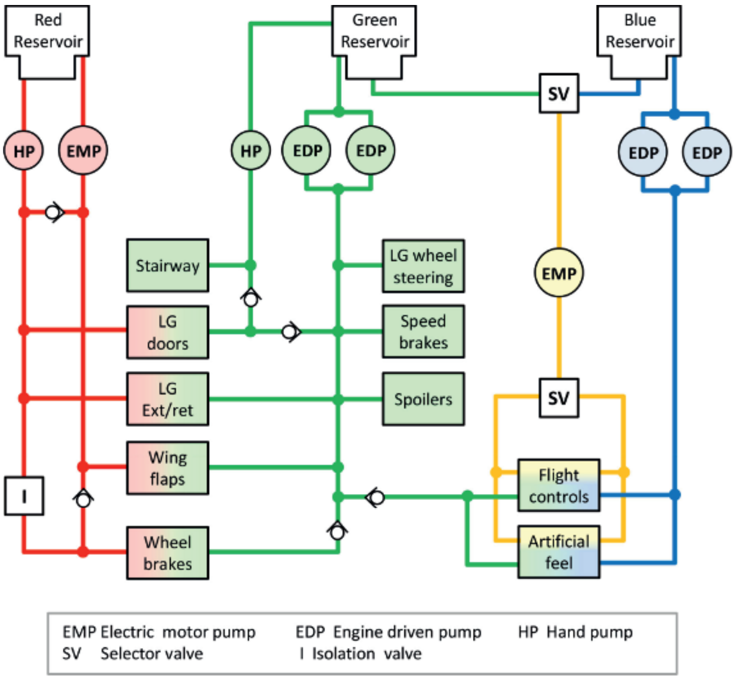


Figure 1.7. *Simplified diagram of the Caravelle hydraulic power generation/distribution architecture (according to [DAR 65]). For a color version of this figure, see www.iste.co.uk/mare/aerospace3.zip*

1.3. The Concorde and flight controls with analog electrical signals and controllers

The first flight of the Concorde (Aérospatiale/British Aircraft Corporation) (Figure 1.8) took place on 2 March 1969. The aircraft was commissioned on 21 January 1976 and withdrawn from service on 2 October 2003. It was the first commercial aircraft on which electrical (analog) technology was implemented for signaling and for the closed-loop control of the primary flight control actuators[4]. To this day, the Concorde is the only supersonic commercial aircraft, reaching over twice the speed of sound (Mach 2.02, or 2,179 km/h) at a maximum altitude of 18,290 m.

4 Control was still analog, but digital computers were needed for the control of air intake from the engines, which was far more complex.

Figure 1.8. *The Concorde (© Air France Archives). For a color version of this figure, see www.iste.co.uk/mare/aerospace3.zip*

This capacity, which is impressive even by the standards of the most recent transonic aircraft (Mach 0.85 cruise speed at 10,700 m altitude), has generated 2 important effects that have motivated the technological shift to *Signal-by-Wire*:

– Kinetic heating. At the cruising speed, the heat generated by friction between air and aircraft increases the operating temperature of structures and systems: 98°C at the wing leading edge and over 90°C at the airframe skin. Materials are subjected to high temperatures that generate thermal expansion deformations reaching several millimeters. This phenomenon strongly influences accuracy and increases the complexity of a solution for mechanical signaling between cockpit and actuators.

– The influence of flight regime on the static and dynamic behavior of the aircraft. The aerodynamic configuration, the ogival delta wing selected for its qualities at supersonic speed, reduces stability at the transonic speed. The trim compensation and control surfaces efficiency vary significantly with the flight regime. The use of multiple elevons, mobile surfaces acting both on pitch (elevator) and on roll (ailerons) and spread along the wing trailing edge requires the implementation of decoupling, synchronization and coordination functions. It dispenses of secondary flight controls (slats, wing flaps, spoilers and airbrakes) some of whose functions are performed by the mobile surfaces of primary flight controls.

Consequently, designers had to resort to electrical technology to transmit the control commands and to elaborate the closed-loop position control of servocontrols. The Concorde thus became the first commercial aircraft with analog “electrical flight controls”. The transmission of position setpoints in a mechanical form has, however, been preserved as an ultimate backup channel, particularly because of the lack of experience in regard to the lightning resistance of critical electrical systems.

1.3.1. *General architecture of flight controls*

As shown in Figure 1.9, the Concorde is equipped with 14 mobile surfaces of primary flight controls: 6 elevons coupled in pairs (inner, middle and outer) on each wing and 2 rudder control surfaces. The flight control system introduces new types of actuators for a commercial aircraft. These are electrohydraulic actuators whose closed-loop control uses analog electrical technology:

– 8 flight control actuators in the strict sense (PFCU for *Powered Flying Control Unit*) located as close as possible to mobile surfaces and position-controlled. One PFCU for each pair of elevons and 1 PFCU for each of the 2 rudder control surfaces;

– 3 *Relay Jacks* (RJ), one for each roll, pitch and yaw axis, located next to the cockpit and position-controlled. These actuators serve for autopilot or as a backup solution for the mechanical relay of pilot commands to the PFCU;

– 3 pairs of actuators for artificial feel, one for each roll, pitch and yaw axis, located next to the cockpit and force-controlled. These actuators provide the pilot with a force feel that is made dependent on flight conditions.

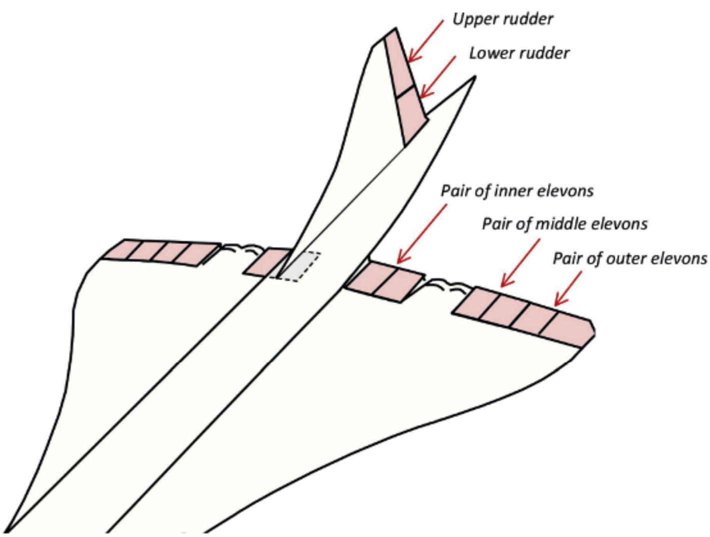


Figure 1.9. *Concorde flight control surfaces (according to [BRI 79])*

For each PFCU, the control system implements 3 position control loops (Figure 1.10, upper image)[5]. The setpoints of the 3 loops, 2 electric (blue and green) and 1 mechanical (M), are elaborated at the cockpit level. They are simultaneously and permanently transmitted to the concerned PFCU(s) (Figure 1.10, lower image).

The auto-stabilization commands elaborated by the analog electric controllers are directly injected in the loops. For that purpose, they are added to the error electrical signal prior to the voltage/current amplification intended for the servovalves.

Moreover, the mechanical control channel in the cockpit involves:

– control of mechanical trim (and of electric trim for pitch control) that operates by position summing on the pilot commands (stick, control wheel or rudder pedals, depending on the axes). Trim control is also a backup channel for elaborating mechanical commands in case of failure of other pilot interfaces;

– an artificial feel device that produces an effort opposing the maneuver on the mechanical control chain in order to restore a muscular feel to the pilot. It involves a passive part comprising a simple spring-based actuator, which is sufficient for rendering an image of aerodynamic loads at low speed and an effect of recalling the interfaces (stick, control wheel, rudder pedals) in the neutral position. For the highest speeds, an active part is made by force-controlled electrohydraulic actuators (see photograph in Figure 1.17 of Volume 2 [MAR 17]). These actuators are associated in load summing and operate in active/standby mode in hot redundancy (see Chapter 2, Volume 1 [MAR 16b]), the actuator named "blue" having priority. Each actuator is an independent chain from the viewpoint of power supply (blue or green hydraulic network) and control (analog computer of artificial feel 1 or 2, equipped with its command channels (COM) and monitoring channels (MON)).

5 It should be kept in mind that, similar to previous volumes, according to the bond-graph formalism, a half-arrow is used instead of a full arrow in order to distinguish between the power view and the signal view. This choice is obviously related to the power level considered.

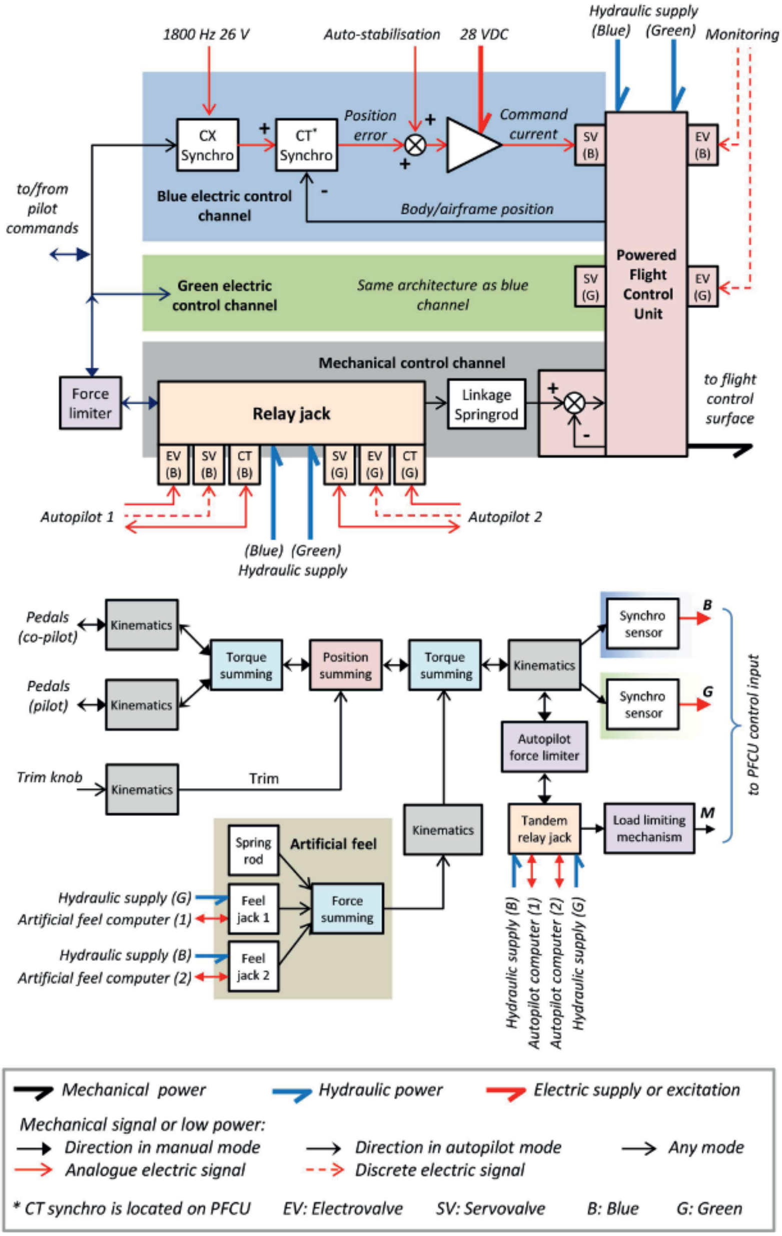


Figure 1.10. *Example of setpoint elaboration for the yaw axis of the Concorde (upper: architecture with 3 loops; lower: generation of position setpoints). For a color version of this figure, see www.iste.co.uk/mare/aerospace3.zip*

1.3.2. *Operation modes*

Information processing and transmission are performed by 2 electrical chains and 1 backup mechanical chain. For each actuator, power metering, management and transmission are realized by hydromechanical chains with electrical control. Power is provided by 2 central hydraulic circuits (blue and green) at a constant pressure of 275 bar (4,000 psi). One backup hydraulic power source (yellow circuit) can replace one of the main sources, except for artificial feel. Control of hydraulic power metering from analog electrical command is allowed by the introduction of metering valves that are dynamic, accurate and only mildly sensitive to vibrations and temperature: the servovalves (see Volume 1, Chapter 5 [MAR 16b]). Actuators operate in hot redundancy: each of the PFCU channels and relay jacks permanently receives control signals. Operation in electrohydraulic mode is activated by an electrical valve that enables the pilot stage of the servovalve to be supplied. In the absence of commands from the electrical valve, the servocontrol operates in pure hydromechanical mode based on the setpoint applied on its input lever. This hot redundancy helps prevent the runaway of servocontrols when a fault occurs: the shift from electrohydraulic mode to hydromechanical mode typically takes only 30 ms.

1.3.2.1. *Manual control in normal mode (Fly-by-Wire)*

PFCU uses electrical setpoints provided by 2 sensors of the synchro-resolver (CX) type. The rotor of these sensors has its position imposed by the pilot through the mechanical chain located in the cockpit. The relay jack controls the position in order to replicate the position requested by the pilot on the mechanical transmission chain to PFCUs, thus providing a backup channel that is immediately available in case of malfunction of electrical channels. The PFCU mechanical input has nevertheless no action in this mode.

1.3.2.2. *Autopilot (Fly-by-Wire)*

When one of the 2 channels of autopilot is engaged through its electrical valve, the relay jack has its input lever position controlled by the electrical commands elaborated by the autopilot analog computers. This position is propagated in the opposite direction, compared to the previous mode, to the rotor of synchro CX and to the cockpit pilot inceptors. A springbox implements a limiting function that bounds the force generated by the relay jack back to the inceptors. This allows the pilot in service to override the autopilot order and regain, if needed, manual control.

1.3.2.3. *Manual control in hydromechanical backup mode (Fly-by-Cable)*

In case of failure of a part in the electrical control loop, the monitoring analog computers cut off the supply of the electrical valve. The servocontrol shifts into hydromechanical mode in order to continue to provide the closed-loop position control function. The transient change is extremely brief as it is sufficient to inhibit the electrical command and to validate the mechanical command, which has not ceased being available.

1.3.3. *Closed-loop analog electrical control*

For these first applications to commercial aircraft, the closed-loop electrical control presented in the upper image of Figure 1.10 capitalizes on the advantages of sensors of the synchro-resolver type. These reliable sensors, not very sensitive to electromagnetic disturbances, make it possible to implement, with no electronics, a function that compares the setpoint (image of the desired output) and the feedback (image of the effective output).

Synchro-resolvers (Figure 1.11) are inductive variable-coupling transformers that output electrical signals representing the angular position θ of their rotor relative to their stator. For a sensor-transmitter (CX), the rotor plays the role of inductor and its angular position θ_c with respect to the stator is the quantity to be measured, which is here the flight control surface position requested by the pilot. It is supplied with constant frequency and voltage (1,800 Hz and 26 V in the case of Concorde) by 3 central power sources (28 VDC). The stator, which is the armature, has 2 windings. These windings provide electrical signals of the same frequency and of voltage proportional to the rotor excitation voltage. The signals represent the sine and cosine of angle θ_c, respectively. The sensor-receiver (CT) has its stator, here the inductor, supplied by bi-phase signals produced by the sensor-transmitter. On Concorde, the stator is mounted on the mobile part of the actuator, which is connected to the driven load. The rotor is angularly positioned (angle θ_m) with respect to the stator by a kinematics that transmits the position of the support structure. Its winding constitutes the armature of the transformer. It delivers a single-phase voltage, whose frequency is identical to the excitation frequency of the sensor-transmitter. The amplitude of this voltage, proportional to the angle $\theta_c - \theta_m$, corresponds to the error signal of the closed-loop control. After conditioning and summing with auto-stabilization orders, the resulting signal is amplified in order to directly supply the actuator power metering element, which is the servovalve of the concerned channel.

The synchros are also used for implementing other functions without electronics:

– 2 synchro transmitters can be connected in parallel and associated with a single synchro transmitter in order to apply a single setpoint to 2 independent closed-loop position controls. Concorde uses this principle for the command of 2 rudder control surfaces (Figure 1.11, upper image);

– the differential synchros (CDX) make possible an addition or subtraction operation for setpoint mixing needs. Concorde uses this principle for controlling the elevons depending on pitch and roll setpoints. The right and left wing elevons are deflected in synchronicity in response to the pitch control and in opposition to the roll control (Figure 1.11, lower image).

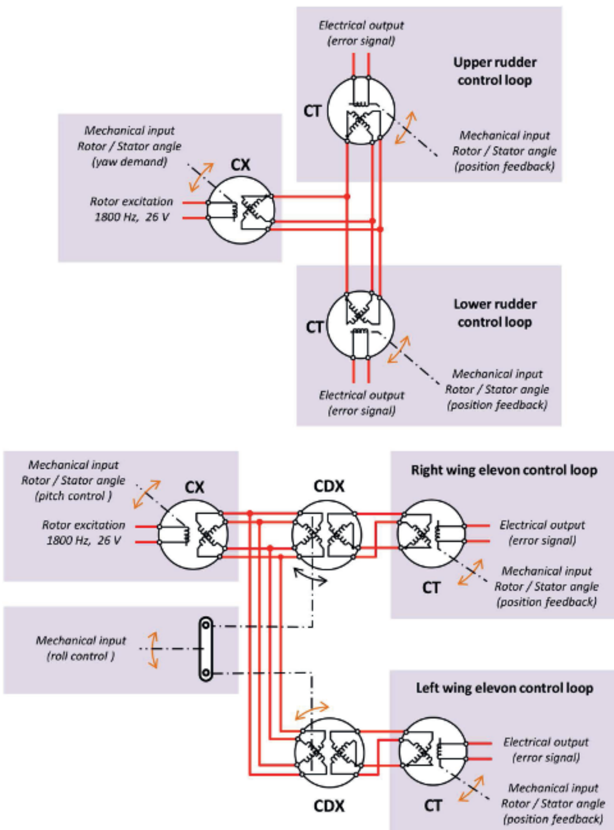


Figure 1.11. *Use of synchros for the elaboration of flight control setpoints. For a color version of this figure, see www.iste.co.uk/mare/aerospace3.zip*

1.3.4. *Relay jack and PFCU*

Relay jacks and PFCU are overall similar with respect to the concepts and technological solutions they implement. They differ in terms of power capacity, which is lower for relay jacks and with respect to the conditions of hydromechanical mode engagement. Figure 1.12 presents the PFCU of an elevon. Each servocontrol has 2 power channels that are associated in tandem and can operate in electrohydraulic or hydromechanical mode. Each of them performs the following functions:

– Transformation of hydromechanical power by a symmetrical double-rod actuator with moving body ❶. The 2 power channels use the same rod and their 2 bodies are connected. Both ends of the PFCU rod are anchored to the support structure. The 2 actuator bodies transmit power to the mobile surface by the intermediary of double-linkage assembly. Due to these 2 load paths, the actuator remains operational in case of breakage of a link or of 1 element of mechanical transmission (*single fail operational*). The relay jacks offer only 1 load path (structural anchorage at only 1 end of the rod, only 1 linkage assembly linked to the body).

– Hydraulic power metering by a linear spool valve ❷. The spools of the 2 channels are mechanically connected. For PFCUs, this allows the limiting of *force fighting* when the 2 channels are active. The 2 channels are never active simultaneously for the relay jacks.

– Power metering control in electrohydraulic mode, by servovalve ❸. The pilot stage of the servovalve controls the opening of the metering valve (in this case, the servovalve power stage) proportionally to its input current.

– Power metering control in hydromechanical mode, by direct control of the metering spool ❹. In hydromechanical mode, the servocontrol achieves hydromechanical closed-loop control of the position whose setpoint is imposed by action on the control lever, (see Figure 7.11 of Volume 1 [MAR 16b]). Similar to the Caravelle's Servodyne, the connection of the control lever to the actuator body and to the metering spool produces a rudder bar effect (see Figure 1.5 of Volume 2 [MAR 17]): the opening of the metering valve results from the relative displacement of the spool with respect to its sleeve, which is connected to the body. Due to these kinematics, the lever mechanically implements the functions of comparison and proportional amplification of the closed-loop control.

– Release and damping of the load in passive mode, by a bypass valve with limitation ❺. In the absence of a hydraulic power supply, the bypass isolates the actuator chambers from the control ports of the metering spool and interconnects them through a hydraulic resistor. This way the concerned channel produces at the level of servocontrol a *fail-safe/fail-damping* type of response that hydraulically damps the body movement with respect to the rod.

– Validation of the electrohydraulic mode by an electrical valve ❻. When it is supplied, the electrical valve authorizes the pressure supply of the servovalve that can control the metering spool. The PFCUs operate with 2 active channels in normal mode (active/active), while the relay jacks have to operate with one single channel (active/standby) to avoid conflicts between the orders of the 2 autopilots.

– Validation of the hydromechanical mode by the clutch of the control lever ❼. The action of the control lever on the metering spools is enabled in the absence of hydraulic power on the 2 channels or when the electrohydraulic modes are not activated by the electrical valves.

– Detection of metering valve jamming by microswitch ❽. The effort required for moving the metering spool (by the lever or by the other spool) is picked up by an elastic element associated with a microswitch. When the level of effort is excessive, the microswitch signals the jamming. The hydraulic supply of the body comprising the jammed spool is then cut off[6]. A spring-based connecting rod is inserted in the kinematic chain that links the output of the relay jack with each of the servocontrols it is associated with (see Figure 1.10, upper image). If one of the control levers is jammed, the relay jack consequently has the capacity to position the input levers of the other servocontrols.

6 There are some differences between relay jacks and PFCUs, as well as depending on the concerned axis in regard to input lever clutching and action following a metering spool jamming. These are not mentioned here.

– Measurement of the body/structure position by the synchros. The position measurement synchros for electrohydraulic mode operation are mounted on the actuator body linked to the driven load. Their rotor is angularly positioned by a specific kinematics that returns the position of the support structure.

The photographs in Figure 1.13 show elements that are important for the supply of PFCU or RJ[7], which are not present in Figure 1.12:

– in order to dispense with hydraulic hoses operating under extended displacements, the PFCUs use telescoping tubes to link the servocontrol body to hydraulic supply and return lines;

– similar to the Caravelle, each channel can also be supplied by the yellow circuit in case the main supply circuit (green or blue) is lost. For this purpose, the pilot has to engage the yellow channel, which then supplies the corresponding servocontrol channel through its shuttle valve.

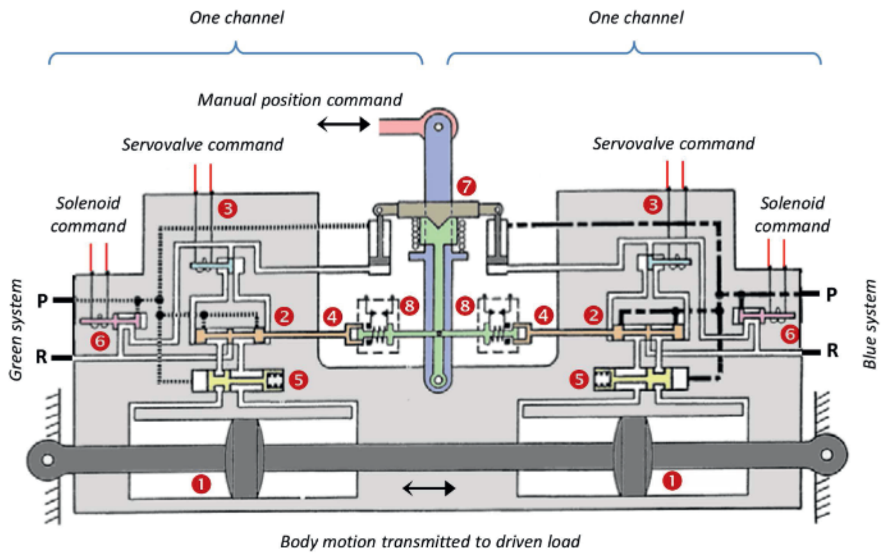
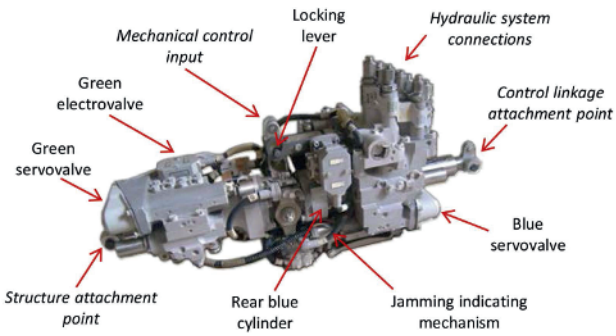


Figure 1.12. *PFCU of the Concorde elevon (according to [BRI 79]). For a color version of this figure, see www.iste.co.uk/mare/aerospace3.zip*

7 The two photographs have different scales.



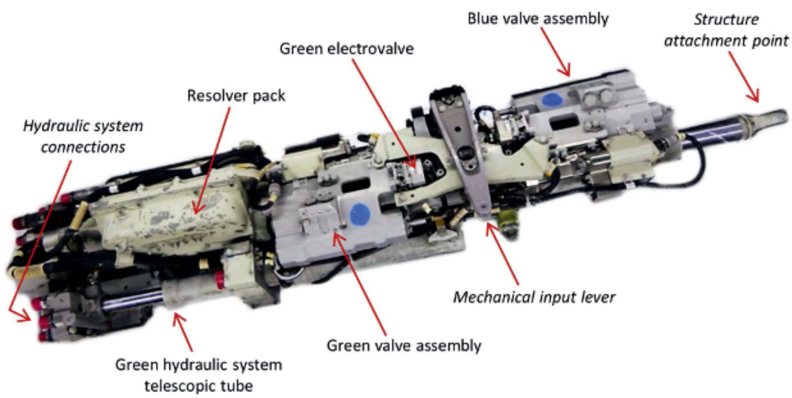


Figure 1.13. *Photographs of Concorde flight control actuators (upper: relay jack (courtesy of Concordescopia Museum, Toulouse); lower: PFCU). For a color version of this figure, see www.iste.co.uk/mare/aerospace3.zip*

1.3.5. *Artificial feel*

Similar to the Caravelle, the use of irreversible flight control actuators deprives the pilots of all muscular feel that may allow them to perceive the stresses to which the aircraft is subjected by the deflection of flight control surfaces. The function of artificial feel actuators is then to return to the pilot a load depending on the flight conditions. For this purpose, the loads produced are elaborated as a function of roll rate for the roll command, air speed and flight control surface deflection for yaw command and, finally, load factor for pitch command. For this latter axis, 3 Hz *wobbler forces* are superimposed on the loads produced in order to warn the pilot if the angle of attack evolves to dangerous values.

Artificial feel function comprises 2 independent channels operating in active/standby mode and hot redundancy mode. The simplified architecture of a channel is presented in Figure 1.14. Each of the channels features an artificial feel computer and an electrohydraulic actuator.

1.3.5.1. *Artificial feel computer*

The artificial feel computer performs several main functions:

a) Force setpoint generator function: depending on the axes, it uses the analog electrical signals provided by the *Air Data Computer* (ADC), the flight control surface deflection, the trim position or the wobbler generator.

b) Closed-loop force control function: it elaborates the servovalve current as a function of force setpoint and force feedback provided by the force sensor. It involves a phase-lead controller and superimposes a 400 Hz dither in order to improve closed-loop control resolution. The dither forces the mobile element of the first stage of the servovalve into permanent dynamic operation, which reduces the impact of nonlinearities (solid friction, magnetic hysteresis, etc.).

c) Monitoring function: it authorizes the actuator operation only if the monitored signals are coherent and within operational range.

d) Supply function: it generates supply, as well as excitation of the force sensor from the 115 VAC central electric network.

1.3.5.2. *Electrohydraulic actuator*

The actuator is supplied by the blue or green central hydraulic network, depending on the channel. Hydromechanical power transformation is performed by a single moving rod actuator whose rear chamber is permanently connected to the return line of the hydraulic network. Power metering is performed by a servovalve that supplies the actuator annular chamber pressure to a level proportional to the control current transmitted by the computer. Force is measured by a dual sensor inserted between rod and load. One of the sensor channels is used for force closed-loop control and the other one for monitoring. The actuator is activated by an electrical valve[8] that authorizes the hydraulic supply of the servovalve. When the electrical valve is not supplied, the 2 actuator chambers are connected to the hydraulic return line. Therefore, due to the dissymmetry of its active sections, the actuator rod gets to the outer end-stop. As the 2 actuators are associated in position summing by a rudder bar, the function is then performed by the other actuator, if activated.

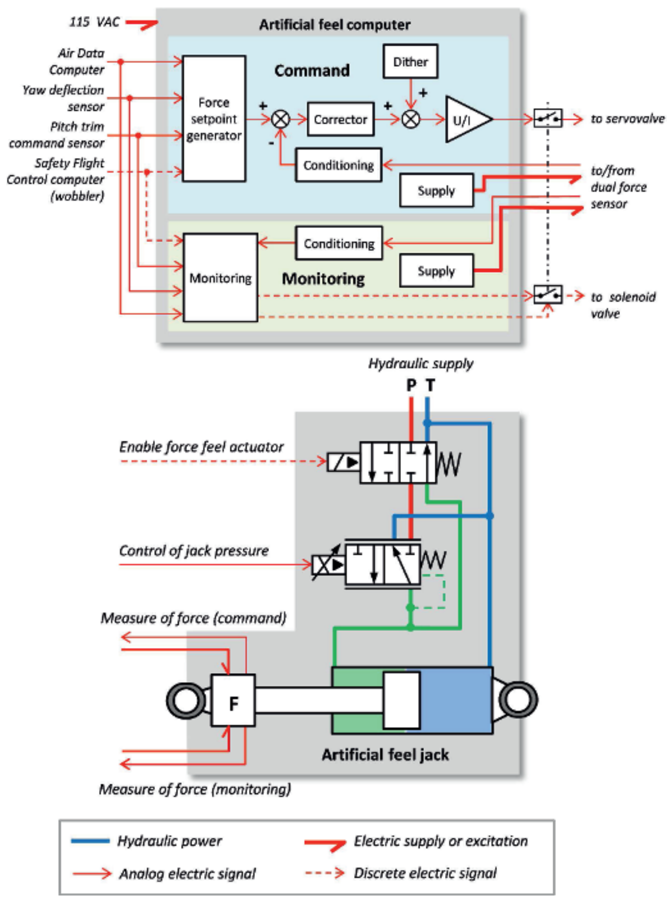


Figure 1.14. *Simplified architecture of the Concorde artificial feel function (setpoint generator inputs depend on the axis considered). For a color version of this figure, see www.iste.co.uk/mare/aerospace3.zip*

8 Both servovalve and electrovalve involve a flapper-nozzle stage.

1.3.6. *Hydraulic power generation*

In the years preceding the design of the Concorde, many fire incidents (Boeing 707 prototype [THO 87], Viscount in 1960, Caravelle in 1963) were caused by the mineral-based hydraulic fluid, MIL-H 5606, whose auto-ignition temperature is only 230°C. This was an argument in favor of using fire-resistant fluids for commercial aircraft. Very low flammability was obtained when using synthetic fluids of phosphate-ester type (trade name Skydrol), which have reached universal use on commercial aircraft for several decades and whose auto-ignition temperatures were much higher. The properties of these fluids were unfortunately not compatible with the operating temperatures expected for Concorde, which could reach 130°C, the upper limit of MIL-H 5606 use. The solution emerged in the form of a fluid that had been purposefully developed for high temperatures and had successfully been used for the American nuclear-armed strategic bomber B-70 [CHU 14]: Oronite M2-V (Chevron). This mineral-base silicate ester has a working range from −60 to 230°C, and its auto-ignition temperature is 404°C.

On Concorde, the operating pressure of 275 bar was adopted for considerations of mass and dynamic response of servocontrols. To supply the actuators with fluid at this pressure, Concorde has 3 hydraulic power networks [TRO 67]: 2 main ones (blue and green circuits) and an auxiliary one (yellow circuit) (Figure 1.15). These networks have a total of 11 pressure-compensated axial piston pumps, with variable displacement:

– 6 pumps driven by engines by means of their accessory gear boxes. Each of the pumps can be isolated from the reservoir by an electromechanically-controlled outer valve. An inner electrical valve makes it possible to also isolate it from the high-pressure pipe to which it is connected. The 4 engines supply the 2 pumps of each circuit (engines 1 and 2 for the blue circuit, 2 and 3 for the green circuit, 2 and 4 for the yellow circuit). Therefore, the 2 hydraulic networks maintain their functionality in case of failure of 2 engines. Even if it does not operate, an engine can continue to drive its pumps by wind-milling. Each pump delivers a maximum of 130 l/min (65 l/min for the yellow circuit) at 3,750 rev/min. Except for take-off and landing phases, only 2 of the 6 pumps are activated (one by the green circuit and another by the blue circuit) as they are sufficient for covering the need. The pumps of the yellow circuit are therefore depressurized. As reserve, they are available power sources that can replace the green or blue power sources at any moment.

– 2 electric pumps exclusively used at ground for maintenance operations. They offer the possibility to selectively pressurize 2 of the 3 hydraulic networks at 241 bar. They are powered by a 115 VAC 3-phase electric network.

– 2 pumps driven by a *Ram Air Turbine* (RAT), an ultimate means to supply the green circuit (266 bar) and yellow circuit (241 bar) in case of engine failure.

– a hand pump for the yellow circuit, accessible only at ground.

Hydraulic power generation of each circuit includes essentially:

a) Fluid conditioning functions: fluid reserve and pressurization are produced by a hydraulic reservoir of maximum volume 27 l (green), 34 l (yellow) and 15.5 l (blue), pressurized at 4.5 bar by the air taken from the engine. Hydraulic liquid is separated from pressurization air by a bellow. A de-aeration device allows the automatic bleeding of the air present on the oil side.

Fluid is cooled by an oil/fuel heat exchanger inserted on the intake line between reservoir and pump, which maintains oil at a temperature ranging between 95 and 105°C.

Fluid filtration is of series type (see Volume 1, section 3.2.3 [MAR 16b]). Filters are connected on the pressure line and on the drain line of each pump, as well as on the return lines to the reservoir.

b) Protection functions: elements of the generic architecture presented in Figure 1.11 of Volume 1 [MAR 16b] can be observed: pressure relief valve, electromechanical isolation valve at pump intake, check valves, etc.

c) Conventional power management and monitoring functions: depressurization of the main pumps, activation of the backup pumps, depressurization of reservoirs for maintenance purposes, monitoring of pressure and temperature, fluid level in the reservoirs, etc.

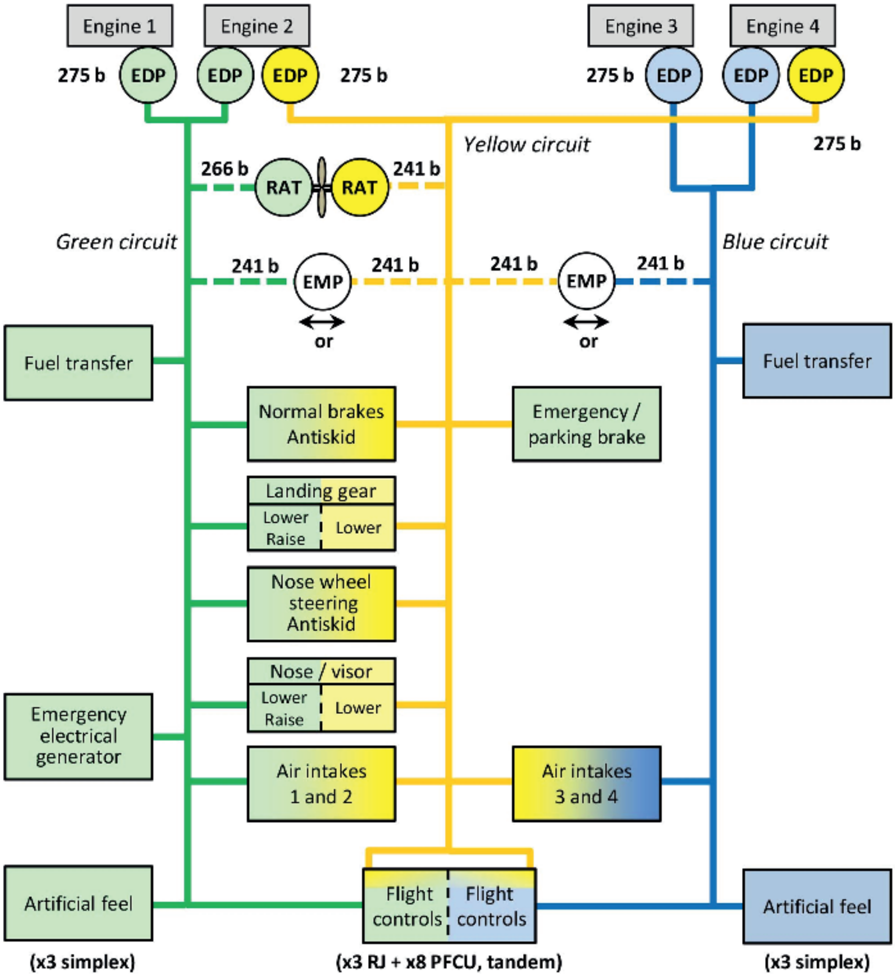


Figure 1.15. *Simplified architecture of the Concorde hydraulic generation and distribution (according to [BRI 79]). For a color version of this figure, see www.iste.co.uk/mare/aerospace3.zip*

It is worth noting that, similar to the Caravelle, the yellow network can be used for emergency supply of actuators of the green or blue network by the control of corresponding selector valves. Consequently, an exchange of fluid takes place between hydraulic networks that are not fully segregated. The actuators concerned by this double supply are represented in Figure 1.15 by 2-colored blocks.