1

General Considerations

1.1. Power transmission in aircraft

1.1.1. *Needs and requirements for secondary power and power flows*

On an aircraft, a distinction is made between primary power, which is used to ensure lift and airborne movement, and secondary power, which is used to power systems (flight controls, avionics, landing gear, air conditioning, etc.). Although much less significant than primary power, secondary power is nevertheless non negligible, as shown in Table 1.1.

Actuation (flight controls and landing gear)	Instantaneous power: 50–350 kW
Cabin lighting	15 kW permanently
Galley	120–140 kW intermittently (warming oven)
	90 kW permanently (cooling)
In-flight entertainment	50–60 kW permanently
Cockpit avionics	16 kW
Cabin air conditioning	190–300 kW

Table 1.1. *Secondary power requirements for a large commercial aircraft [COM 05]*

Power is generally conveyed from sources to users by redundant networks in electrical, hydraulic and pneumatic form. For a typical 300 seat aircraft, these networks are estimated to respectively transmit a power of 230 kVA, 230 kW and 1.2 MW.

Figure 1.1 illustrates the complexity of secondary power networks for a single-aisle aircraft of the Airbus A230 type [LIS 09]. On this diagram, power flows from power generators situated on the inner ring, through distribution networks located around the intermediate ring, to power users gathered on the third ring. The outer ring depicts the surrounding air which is considered here as being equivalent to a thermal power source. Power flows are depicted by colored arrows whose colors indicate the nature of the power involved.

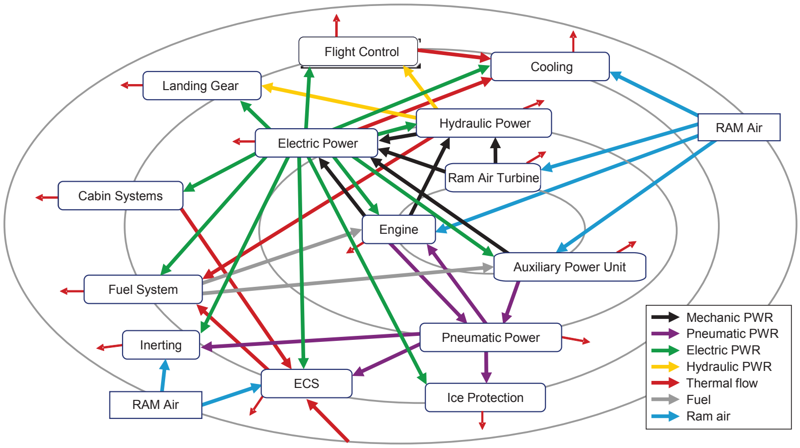

Figure 1.1. *Secondary power flows for an Airbus A230 type single-aisle aircraft [LIS 08]. For a color version of the figure, see www.iste.co.uk/mare/aerospace1.zip*

1.1.2. *Actuation functions*

A function can be defined as the act of transforming matter, energy or data in time, shape or space [MEI 98]. In practice, the perspective from which a function is viewed depends on the engineering task at hand. For instance, for the purpose of power scaling, the actuation function can be viewed as the transformation of power received at the source into power transmitted to the load; this transformation takes place both in shape (e.g. hydraulics toward translational mechanics) and in space (aspect of power transmission from point A to point B). In contrast, when designing flight controls, the actuation function is considered as the act of converting a signal (e.g. an electrical command for positioning a load) into another signal (current position of the load).

Power requirements for actuation are numerous and diverse. They essentially concern the following.

– *Primary flight controls*

The purpose of primary flight controls is control of aircraft trajectory. On a conventional aircraft, as the one pictured in Figure 1.2, they take the form of control surfaces responsible for controlling the three rotational degrees of freedom: the ailerons for roll, the rudder for yaw and the elevator for pitch.

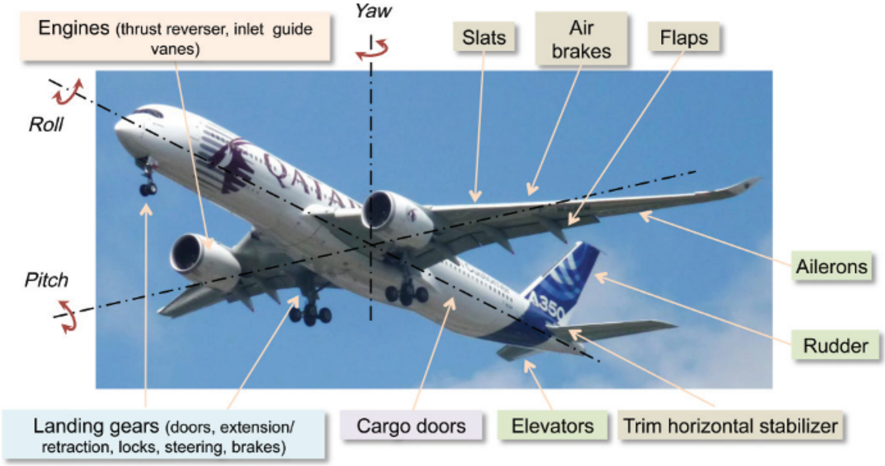

Figure 1.2. *Actuation needs on a commercial aircraft*

As for helicopters, they offer four degrees of freedom. Helicopter flights are controlled by acting:

– on the swashplate, Figure 1.3. The swashplate translation with respect to the rotor axis makes it possible to collectively act on the pitch of the blades in order to act on the intensity of the lift vector generated by the main rotor. Tilting the swashplate about the two axes perpendicular to the rotor axis causes the pitch to vary cyclically (pitch of the main rotor blades during one rotor revolution). In turn, this allows the rotor lift vector to be tilted about the roll or the pitch axis;

– on the collective pitch of tail rotor blades for yaw control.

Figure 1.3. *Swashplate actuation on an AS332 helicopter*

Convertible aircraft such as Boeing V22 or Agusta-Westland AW609 also put to use the nacelle tilt about the pitch axis.

– on launchers (as well as on fighter aircrafts with thrust vector control feature), the thrust force generated by the booster or the jet engine is steered about the yaw and pitch axis in order to direct the thrust vector according to the desired trajectory;

– mechanically signaled flight controls also rely on actuators to superimpose on the pilot's setpoint, the demands of the autopilot as well as stability and control augmentation commands.

– *Secondary flight controls*

Secondary flight controls make it possible to modify the aerodynamic configuration during particular flight phases. On conventional aircraft, slats and flaps increase the chord and curvature of the wings. This is done to increase the lift of wings at low speeds and therefore decrease the takeoff or landing speeds. Airbrakes (also called spoilers) reduce aircraft speed by increasing aerodynamic drag. Trim tabs, for instance the trimmable horizontal stabilizer, ensure the global equilibrium of the aircraft during the given rectilinear flight phases (e.g. climb, cruise or approach) so that primary flight controls operate around their neutral position on average.

– *Landing gears*

These require numerous actuation functions:

– for raising or lowering landing gear by sequencing the opening or closing of doors, extending or retracting the gear and locking it in a raised or lowered position;

– for steering the wheels in order to ensure steerability on the ground during taxiing;

– for wheel braking in order to dissipate as heat part of the kinetic energy associated with the horizontal speed of the aircraft (in addition to airbrakes and thrust reversers during landing). Left/right differential braking can also contribute to improve steerability on the ground;

– also worth mentioning, landing gear struts are autonomous hydropneumatic components. Upon touchdown, they absorb the kinetic energy associated with the vertical speed component of the aircraft with respect to the ground.

– *Engines*

Engines also rely on actuators to steer inlet guide vanes on the turbine stator, to deploy or stow thrust reversers, to operate maintenance panels, to modify the geometry of air intakes or nozzles, or even to control propeller blade pitch.

– *Utilities*

Other actuators are also used, for example, to operate cargo doors (and passenger doors on new large aircraft such as Airbus A380 and Boeing 787), rotor brakes for helicopters, winches, weapon systems (aiming guns, raising or lowering the arresting hook, etc.) among other things[1].

1.1.3. *Actuation needs and constraints*

The solutions implemented for actuation in aeronautics and space have to meet numerous requirements and comply with the following strict constraints.

1 The supersonic transport Concorde aircraft also used nose lowering actuators to give pilots an unblocked view of the runway.

– *Type of mission*

On the flight timescale, the need for actuation can be seen as continuous, such as, for example, the need for primary flight controls. However, this need can also be considered transient, meaning that it only exists during a minor portion of the mission. For example, this is the case for the landing gear steering function or for secondary flight controls. Lastly, the need for actuation is said to be impulsive when it only appears for a very short amount of time. An example of this is landing gear unlocking.

– *Controls*

The vast majority of actuators are closed-loop position controlled (e.g. for flight control surfaces or for steering nose landing gear). Although it is less frequent, they can also be closed-loop speed controlled (e.g. to drive back-up electric generator hydraulically) or even closed-loop force or pressure controlled (e.g. for braking). Additionally, some controls can be of the on/off type, such as, for example, landing steering locks.

– *Power and dynamics*

Summed up in Table 1.2 are examples of power and dynamics needs as a function of the type of aircraft.

Actuation function		Typical range	Aileron Airbus A320	Nose landing gear steering Airbus A320	Tiltrotor BoeingV22 OspreyMode conversion	Thrust vector control Ariane V
Stroke	(mm)	20–700	44		1143	±160
	(degree)			±75		
Speed	(mm/s)	20–500	90 no-load		97	972 no-load
	(degree/s)	10–90		20		
Force	(kN)	20–350	44		80	347
	(Nm)			7000		
Bandwidth (Hz)		1–20	≈ 1	≈ 1.5	3.2	7.9

Table 1.2. *Examples of power needs*

It is important to keep in mind that the power consumption of actuation functions indicated here corresponds to the worst case scenario. In reality, under normal circumstances, actuation functions are operated well below these extreme values. Figure 1.4 illustrates this statement for the actuator of an Airbus A320 aileron. It can clearly be seen that during the course of a typical mission, only −80 to 20% of the available force and ±15% of the available speed are used (except checklist).

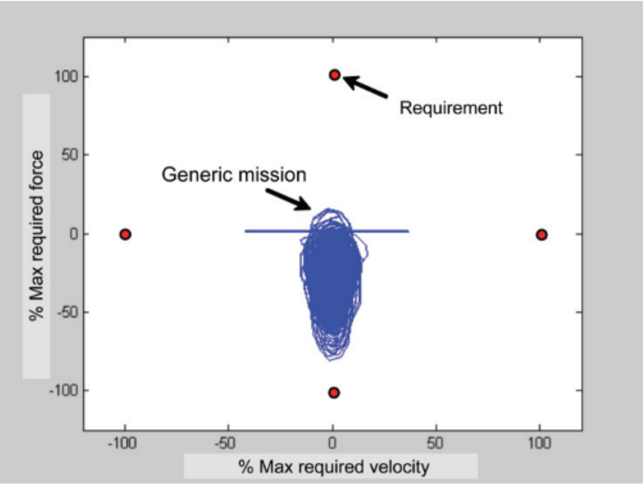

Figure 1.4. *Power requirement for the actuator of an Airbus A320 aileron [MAR 09]*

– *Environment*

Actuators are exposed to harsh climate conditions (pressure, temperature and humidity) as well as harsh electromagnetic (interference and lightning) and vibration environments. Every time they fly, actuators undergo a pressure and temperature cycle. For instance, at the cruising altitude of a jet (10,360 m or 34,000 ft), absolute pressure is only as high as 250 mbar and the temperature drops to −52.3°C (for a standard atmosphere [ICA 93]). Regarding hydraulics, the major constraint faced is maintaining the fluid temperature in its normal operating range. For example, actuators must be functional between −60°C and +100°C and they must be operational, meaning achieving full performance, between −40°C and +70°C.

– *Lifespan*

The lifespan of aircraft typically varies from 5,000 flight hours for fighter jets to more than 100,000 flight hours for new commercial aircraft (10,000 h for a NH90 helicopter, 48,000 h for the first Airbus A320 aircraft, 140,000 h for an Airbus A380). This lifespan generally corresponds to operating over the course of 30–40 years.

– *Reliability*

The acceptable probability of a failure depends on the criticality of the function to be performed (see Chapter 2). Since actuators often contribute to critical functions, tolerated failure rates are extremely low. For example, for primary flight controls, one catastrophic event is tolerated per 1 billion flight hours in commercial aeronautics. This major constraint heavily impacts the architecture of actuation systems. These systems therefore most often have to be redundant in order to respond to failure as required.

– *Maturity*

Maturity is a strong sales argument that directly impacts operational readiness. Concerning new commercial programs, the objective is to reach 99% on-time departures or with delays due to technical difficulties not exceeding 15 min.

– *Topology*

On aircraft, several dozen actuators are generally implemented and can be located dozens of meters away from their power source. Weight, position and performance of the power delivery network are therefore heavily impacted by the spatial layout of hydraulic systems. On an Airbus A380, there is, for example, more than 40 flight control actuators [MAR 04], some of them located more than 60 m away from the hydraulic power generator.

1.2. Primary and secondary power transmission functions for actuators

Generally speaking, the main functions associated with power transformation and metering[2] are clearly identifiable (see Chapters 4 and 5).

2 Power metering is also known as "control of power".

Conversely, when dealing with actuation solutions, other significant functions are often neglected even though these functions turn out to be the most difficult to master in practice. It is therefore essential to pay close attention to:

– reversibility, a concept which makes it possible for a passive actuator, for example, to let itself be driven by an active actuator through the load they share;

– protection against excess static and dynamic force, which restricts mechanical stress/strain on control surfaces or on the airframe, for example, during sudden gusts of wind;

– cooling or heating in order to maintain actuator temperature within its normal operating or functional range;

– damping, to dissipate energy and avoid resonance. For instance, to avoid shimmy[3] of the nose landing gear steering;

– Dissipation of the energy to be absorbed when reaching the end-stop. For example, this is important for thrust reversers;

– force equalization, which is intended to ensure that actuators equally share the responsibility of driving a single load without force-fighting. For example, for the three active actuators of a single rudder;

– motion synchronization, which aims to position identically and at all times independent loads, each fitted with their own actuator. For example, for two independent panels of a single thrust reverser;

– locking in position, de-clutching or returning to a neutral configuration depending on the desired response to failure;

– maintenance or diagnosis. For example, with the purpose of isolating part of the system to detect and measure a possible internal leak.

In order to bring structure to this study of architectures, it is useful to define and distinguish the primary functions and secondary functions. A detailed investigation of these functions and the technological or conceptual architectures that enables their implementation will be provided in the following chapters regarding hydraulically powered actuators.

3 Sustained vibration of landing gear in rotation about the gear strut axis [CUR 88].

1.2.1. *Primary functions*

The general structure of the architecture of a power transmission system can be represented by the diagram in Figure 1.5 [CND 02]. Flows of information (signal component) are distinguished from flows of energy (power component) on the schematic.

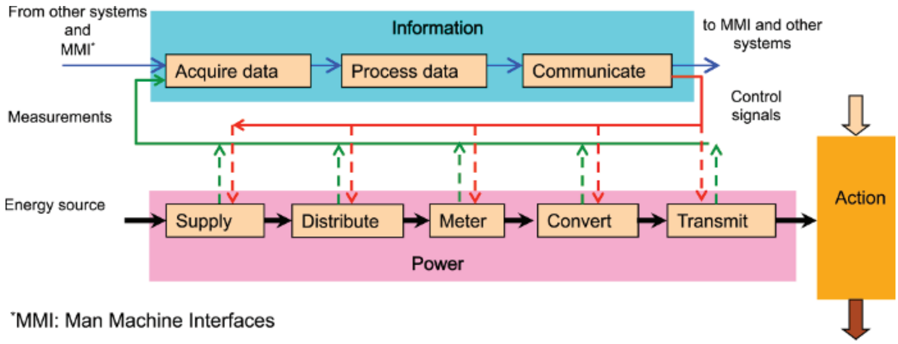

Figure 1.5. *Functions in the information and power chains [CND 02]*

According to this representation, power architecture involves five key functions: to supply, distribute, meter, convert and transmit. This interesting schematic point of view calls for a number of comments:

1) On the path between sources and users, generic functions of the power chain can appear several times and in a different order.

2) On this diagram, the signal architecture is explicitly separated from the power architecture. However, interface functions between the signal and the power components ("measure" and "apply command") are not mentioned.

3) The information chain can additionally include monitoring functions (usage, diagnosis and prognosis).

4) Within aerospace actuating components and systems, signal and power functions are often performed hydromechanically for the sake of simplicity, compactness and reliability. This partition of signal and power is often hard to see, all the more since it is seldom emphasized in the schematics of technical documents. This aspect will be noticeable in several examples over the course of the next chapters.

5) In order to perform its functions, the information chain also requires a power supply; for instance, to power flight control computers. Therefore, it can also be seen as a power chain if interested in this perspective: such as when the chain is used to assess the thermal equilibrium of electronic cards or to assess consumption in case of loss of the normal power supply. It is essential to keep this in mind while designing architectures, especially with respect to reliability requirements.

6) Misunderstandings often arise from the interpretation of the word actuator. Indeed, the meaning of this word is different from one community to the other. For instance, in the IEEE (Institute of Electrical and Electronics Engineers) community, an actuator often represents the component that converts power between electrical and mechanical domains, typically an electric motor. In the field of aeronautics, an actuator is instead loosely defined as the physical device that the aircraft manufacturer is provided with and integrates in the aircraft to carry out the actuation function. Depending on the level of integration, the "actuator" can include power metering, power transmission and even control functions in addition to its power converting function. For example, the actuator of an Airbus A350 aileron WXB introduced in Figure 1.6 incorporates both power and position control chains.

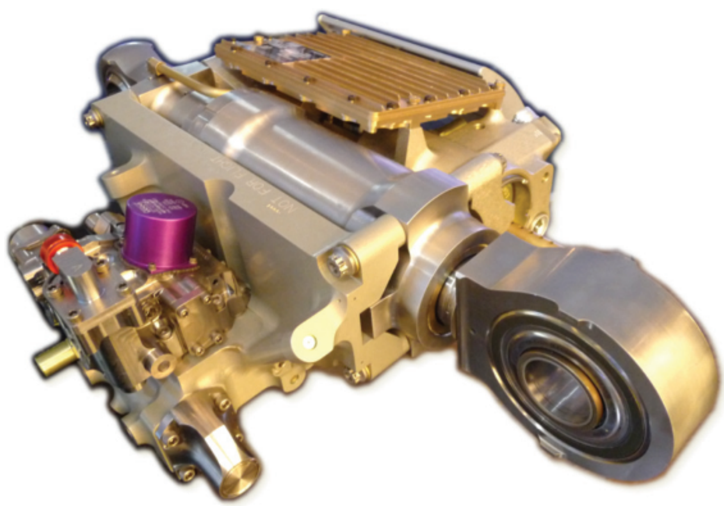

Figure 1.6. *Airbus A350 XWB aileron actuator incorporating position control electronics*

1.2.2. *Secondary functions*

In practice, the power section performs many secondary functions, the significance of which is far from minor. As a matter of fact, these secondary functions are the ones that cause the most specification, design and maintenance issues. They are essentially linked to safety and to power management depending on the mode of operation. Key secondary functions are as follows:

– *Concentrate.* Several power sources are combined to feed one or more users, while avoiding interactions between sources. For example, several pumps can feed a hydraulic power network.

– *Divide.* The power supply is divided between several users, depending on demand or following a given proportion. For example, a single network feeds several flight control actuators.

– *Isolate.* The component is isolated from the rest of the power circuit. For example, the system responsible for extending the landing gear does not need to be powered during cruise.

– *Restrict.* Onboard systems are protected from excessively high values, and sometimes also from excessively low values of variables associated with power transfer. For example, the hydraulic network pressure is limited in the event that the constant pressure regulation of hydraulic pumps fails.

– *Ensure irreversibility.* Power propagation is enabled in only one direction, generally from the source to the load. This makes it possible to freeze the trimmable horizontal stabilizer in position in the event that the actuation fails, for example.

– *Prioritize power supply.* In case of low power, power supply to non-essential users is cut. For example, primary flight controls are prioritized over landing gear extension that, as a consequence, is left to extend under its own weight.

– *Store and restore energy.* Energy is stored and restored according to demand and mode of operation. For example, to maintain the parking brake active after engines are switched off.

– *Condition hydraulic fluid.* Hydraulic fluid is maintained in good condition to ensure it is able to properly carry out all required functions (power transmission, lubrication and heat transfer).

1.2.3. *Signal approach and power approach*

When a signal approach is adopted, it is implicitly assumed that the element on the receiving end of the signal has no impact whatsoever on the signal it receives. This approach is interesting from a functional point of view. However, it soon starts showing flaws when considering power transmission systems. Indeed, no matter the physical domain, power that flows along a functional link is the product of two power variables. And these variables are linked by elements located at the source and at the end destination of the power link. Table 1.3 summarizes power variables for electric, mechanic and hydraulic domains. Useful energy variables and units are also indicated in the table.

	Power variables		Useful energy variables
	Effort variable	Flux variable	Flux integral with respect to time
Electrical	Voltage (V)	Current (A)	Electric charge (C)
Mechanical			
Translation	Force (N)	Linear velocity (m/s)	Linear position (m)
Rotation	Torque or moment (Nm)	Angular velocity (rad/s)	Angular position (rad)
Hydraulic	Pressure (Pa)	Volume flow rate (m^3/s)	Volume (m^3)

Table 1.3. *Power and energy variables*

On architecture schematics, it would be interesting to explicitly indicate which of the two approaches, signal or power, has been adopted by using a different graphical representation for each. The two approaches could, for example, be differentiated by making lines representing power flows thicker compared to information flows lines. Furthermore, the physical domain concerned could be highlighted by associating it with a specific color.

1.2.4. *Types of actuators*

Denomination of aerospace actuators is determined both by the technological domain (mechanical, hydraulic or electrical) used for interfacing them on the signal level (controls and measurements) and used for their power supply. Regarding solutions powered electrically, the technological domains (hydraulic or simply mechanical) used within the actuator to convert electrical power into mechanical power have to be even further specified. Table 1.4 summarizes the main types of actuators that are encountered in aircraft. Uppercase letters M, H and E represent the different types of technologies: M for mechanical, H for hydraulic and E for electrical.

Signal Interface	Interface and internal power conversion	Most common denomination
M**	M*	Manual
M**	H → M	Hydromechanical (HMA stands for Hydro Mechanical Actuator)
E***	H → M	Servo-hydraulic (HSA stands for Hydraulic Servo Actuator)
E	E → H → M	Electro-hydrostatic (EHA stands for Electro Hydrostatic Actuator)
E	H → M (normal) E → H → M (backup)	Servo-hydraulic with electro-hydrostatic backup (EBHA stands for Electric Backup Hydraulic Actuator)
E	E → M	Electromechanical (EMA stands for Electro-Mechanical Actuator)
E	H → M (normal) E → M (backup)	Hydraulic with electromechanical backup (EBMA stands for Electrical Backup Mechanical Actuator)

* Optionally control tabs can provide assistance by aerodynamic force to flight controls
** Optionally with additional control signals generated hydraulically or electrically (autopilot, stabilization, etc.)

*** Optionally with mechanical backup

Table 1.4. *Types of actuators according to the nature of their signal and power interfaces*

The following paragraphs will further describe the actuators introduced in Table 1.4.

– *Manual actuation*

When actuation is carried out manually, it can be aerodynamically assisted for power, by using control tabs for example [ROS 00]. Furthermore, manual actuation can be assisted from an information standpoint by secondary actuators, such as when performing an autopilot (Figure 1.8) or stabilization function.

– *Hydromechanical actuators (HMA)*

Hydromechanical actuators (HMA) have been the “go-to” actuators for aircraft up until the emergence of electrical controls, such as those chosen for Airbus A300-600 spoilers. With very few recent exceptions, flight controls of helicopters still use this type of actuator.

– *Hydraulic servo actuators (HSA)*

The emergence of computerized electrical controls was made possible by the development of hydraulic servo actuators (HSA). Indeed, within these actuators, a servovalve serves as a power interface between electrical and hydraulic domains. Airbus A320 was the first ever commercial aircraft to be fitted with HSA and it initiated the universalization of these new actuators for flight controls. However, at the time, these servo actuators were the first of their kind and therefore still retained a mechanical backup for the information chain of certain actuators, such as the mechanical backup that was entirely removed from Airbus A380. Electrically controlled actuators have become widespread for flight controls as well as for braking and landing gear steering.

– *Electro-hydrostatic actuators (EHA)*

Over the past decade, electro-hydrostatic actuators (EHA), that are powered electrically, have appeared. EHAs transmit power to the load through a hydrostatic loop which involves, within the actuator, an electric motor, a pump and a hydraulic cylinder. These solutions are used as backup actuators for the time being, such as on Airbus A380, A400M and A350 XWB aircraft.

– *Electro-hydrostatic backup servo-hydraulic actuators (EBHA)*

Airbus A380 also introduced electro-hydrostatic backup servo-hydraulic actuators (EBHA) that operate as servo-hydraulic actuators in regular mode and as electro-hydrostatic actuators in backup mode. As a consequence, they are supplied both by hydraulic power and by electrical power.

– *Electromechanical actuators (EMA)*

Electromechanical actuators (EMA) combine an electrical motor with mechanical transmission. Their use is still not very widespread when it comes to performing high power critical functions due to the lack of maturity of certain of their functions. Boeing B787 relies on EMAs for 4 out of 14 spoilers and for wheel braking.

Technological solutions for power transmission within the actuator can be combined in different ways [MAR 11]. For example, in order to implement a backup mode dissimilar from the normal mode, in Airbus A400M, landing gear doors are driven by electromechanical backup hydraulic actuators (EBMA).

This first volume is focused on mechanical power transmission using hydraulic technologies. Most or all electrical solutions, both on the signal level and on the power level, will be addressed in the second volume of this series. Mechanical to mechanical power conversion – even though it can be found in certain actuation functions powered hydraulically – will also be addressed in the second volume.

1.3. Hydraulic power actuation

The following section provides a quick introduction and overview of hydraulically powered actuation, which will then be further detailed in the next chapters.

1.3.1. *Units and reference values*

Table 1.5 summarizes the symbols and units used in power hydraulics. As is very often the case, international systems of units (SI units) have the benefit of constituting a homogeneous unit system. However, they are ill-suited for quick manual calculations and they hamper the mental representation of physical quantities. "Engineering" units, which include metric (excluding SI units) and imperial units, make up for this disadvantage by scaling down SI values of physical quantities "to a human level", meaning these scaled values typically vary from 0.1 to 1,000. However, such units should be used with care because they do not constitute a homogeneous unit system for calculations. Therefore, if not used to deal with such units, it is best to carry out calculations using SI units and then to convert results into "engineering" units (metric or imperial) to assess their plausibility and communicate with experts on these results.

	Pressure	Volume flow rate
Symbol	P	Q
SI Units	Pascal (Pa or N/m²)	m^3/s
Metric Units (excluding SI units)	bar (1 bar = 10^5 Pa)	l/min (1 l/min = 1/60,000 m^3/s)
Imperial Units	pound/inch² (psi) 1,000 psi = 69 bar	$inch^3/s$ (cis) 1 cis = 0.983/min gal/min (gpm) 1 gpm = 3.785 l/min

Table 1.5. *International and common units used in the field of hydraulics*

If the fluid is assumed to be incompressible and of constant temperature, then power $\mathcal{P}$ supplied by the fluid between two points 1 and 2 of a circuit is given by:

$$\mathcal{P} = Q(P_1 - P_2) \qquad [1.1]$$

A quick calculation can be carried out using "trade" units by introducing a homogeneity factor of 600:

$$\mathcal{P}_{\mathrm{kW}} = Q_{\mathrm{l/mn}}(P_1 - P_2)_{\mathrm{bar}}/600 \qquad [1.2]$$

1.3.2. *Energy transport by a liquid*

There essentially exists four ways of transporting energy using an incompressible fluid: by varying its altitude, its velocity, its pressure or its temperature.

– *Gravity transport*

When raising the altitude of an incompressible liquid by a quantity z (m), its gravitational specific energy $\overline{E}_g$ (J/kg) is increased by:

$$\overline{E}_g = gz \qquad [1.3]$$

where g (m²/s) is the acceleration due to gravity.

For example, for an increase in altitude of 5 m on Earth where g = 9.81 m/s², the gravitational potential energy of 1 kg of fluid increases by 49 J. This solution is widely applied in hydroelectric power plants. However, it is not applicable in most other applications because the variation in altitude is relatively weak and is enforced by geometric considerations. The effect of gravity is therefore considered as a disturbance. Indeed, between two points of the same hydraulic line spaced apart by an altitude difference z, the gravity effect induces a pressure difference:

$$\Delta P_g = \rho g z \qquad [1.4]$$

where ρ (kg/m^3) is the specific density of the fluid.

For example, on the same return line of a commercial airplane, the pressure at a rudder actuator is typically lower by 1 bar than the pressurized reservoir pressure, assuming the latter is located 10 m lower (ρ= 1,020 kg/m^3).

– *Transport in (hydro)kinetic form*

When increasing the velocity of an incompressible liquid from v_1 to v_2 (m/s), its hydrokinetic specific energy $\overline{E}_{hc}$ is increased by:

$$\overline{E}_{hc} = \frac{1}{2}(v_2{}^2 - v_1{}^2) \qquad [1.5]$$

For example, a fluid domain that goes from zero to 10 m/s acquires 50 J/kg of hydrokinetic specific energy.

Therefore, in order to be of interest, energy transmission in kinetic form has to involve high speeds. Unfortunately, high speeds generate significant pressure drops in lines and give rise to loud noise and significant dynamic phenomena[4]. As a consequence, energy transmission in kinetic form is hardly ever implemented. Furthermore, converting kinetic energy into pressure energy is a very inefficient process. This contributes to further minimizing the benefit of power transport in hydrokinetic form.

– *Transport in hydrostatic form*

When raising the pressure of an incompressible liquid by a quantity ΔP (Pa), its hydrostatic specific energy $\overline{E}_{hs}$ is increased by:

$$\overline{E}_{hs} = \frac{\Delta P}{\rho} \qquad [1.6]$$

Consider a standard pressure difference of 200 bar and a specific density of 1,000 kg/m^3, in these conditions 1 kg of liquid has a pressure energy equal to 20,000 J.

Therefore, compared to the two previous transport methods described, energy transport in hydrostatic form reduces the required fluid mass four hundred fold!

– *Transport in heat form*

When raising the temperature of an incompressible liquid by a quantity $\Delta\Theta$ (°C), its heat specific energy $\overline{E}_{\Theta}$ is increased by:

$$\overline{E}_{\Theta} = C_p \Delta\Theta \qquad [1.7]$$

where C_p is the heat capacity of the hydraulic fluid (J/kg/°C).

When 1 kg of liquid, with a specific heat equal to 1,900 J/kg/°C, undergoes a temperature increase of 10°C, its heat energy increases by 19,000 J.

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4 For this reason, fluid velocity in lines is limited to a few meters per second.

For the purpose of actuation, the main goal is to transport energy using liquid in order to, in the end, make it possible to apply a sufficiently large force on mechanical loads at low speeds. This is why the following three concerns argue in favor of energy transport in hydrostatic form:

– as for kinetic energy, converting heat energy into hydrostatic energy is a very inefficient process. However, this is not the case for the reverse process;

– regarding positive displacement hydraulic-mechanical power transformers (cylinders, pumps and motors), force is functionally proportional to pressure and velocity is functionally proportional to volume flow rate. Therefore, it is "natural" to transport energy in pressure form since it is required to transmit large forces;

– the temperature difference possible to harness and exploit for energy transmission in heat form is extremely small when aiming to cover the entire operating range of the aircraft.

Table 1.6 gives an example to illustrate the benefit of transporting energy in hydrostatic form. The masses of fluid consumed by each means of energy transport are compared. This comparison is carried out under the assumptions that: an aircraft rudder has to be steered 1° and that this requires the application of an average moment of 800 Nm, which corresponds to an energy of 14 J. It is also assumed that conversions are 100% efficient.

	Hypothesis	Specific energy (J/kg)	Consumed fluid mass (g)	Comments
Gravity	$g = 9.81$ m/s² $z = 5$ m	49.05	285	Height imposed by geometric considerations
Hydro-kinetic	$v_1 = 0$ m/s $v_2 = 10$ m/s	50	280	Poor efficiency of the conversion process of velocity energy into pressure energy
Hydro-static	$\Delta P = 200$ bar $\rho = 1000$ kg/m^3	20,000	0.7	Solution implemented Excellent efficiency of the conversion process of pressure energy into kinetic energy
Heat	$\Delta\Theta = 10$°C $C_p = 1900$ J/kg/°C	19,000	0.738	Very poor efficiency of the conversion process of heat into work

Table 1.6. *Benefit of transporting energy in hydrostatic form*

Even without taking into account the efficiency of conversion processes, the benefits of transporting energy in hydrostatic form are obvious. Since the mass of fluid required for transporting and converting power is directly proportional to the differential pressure, it is clearly beneficial to elevate working pressures, at least from the point of view of the fluid. In practice, this pressure raise is limited by several effects. First, the thickness of sleeve casings (lines, pipes, cylinders, etc.) must be increased in order to resist higher mechanical stresses. Second, a raise in pressure – which allows for lines with smaller diameters – increases fluid inertia which, in turn, increases the amplitude of the dynamic phenomena it gives rise to. Finally, a pressure raise requires a great command of sealing and lubrication technologies in order to ensure the lifespan and reliability required. At any given time, the acceptable working pressure is defined by the balance of all these considerations.

REMARKS.–

– From the previous equations it is possible to carry out simple calculations to obtain orders of magnitude. If converting hydrostatic energy into hydro-kinetic energy is performed with 100% efficiency, free flow from a pipe at 200 bar to the open of an incompressible liquid of specific density 1,000 kg/m^3 generates a speed of 200 m/s. Furthermore, if the stream is vertical, the fluid rises up to 2,000 m high, given that the conversion of hydrostatic energy into hydro-kinetic energy is also perfect. Conversely, if all the pressure energy is dissipated as heat transmitted to the liquid flowing through a restriction, the temperature of the liquid increases by 10.5°C for a fluid with a heat capacity of 1,900 J/kg/°C.

– Since a liquid can never be rigorously incompressible, it is interesting to quantify the energy associated with its elastic deformation. For a pressure increase ΔP, a fluid with an effective Bulk modulus B stores, because of its deformation, a specific energy equal to:

$$\overline{E}_c = \frac{\Delta P^2}{2\rho B} \qquad [1.8]$$

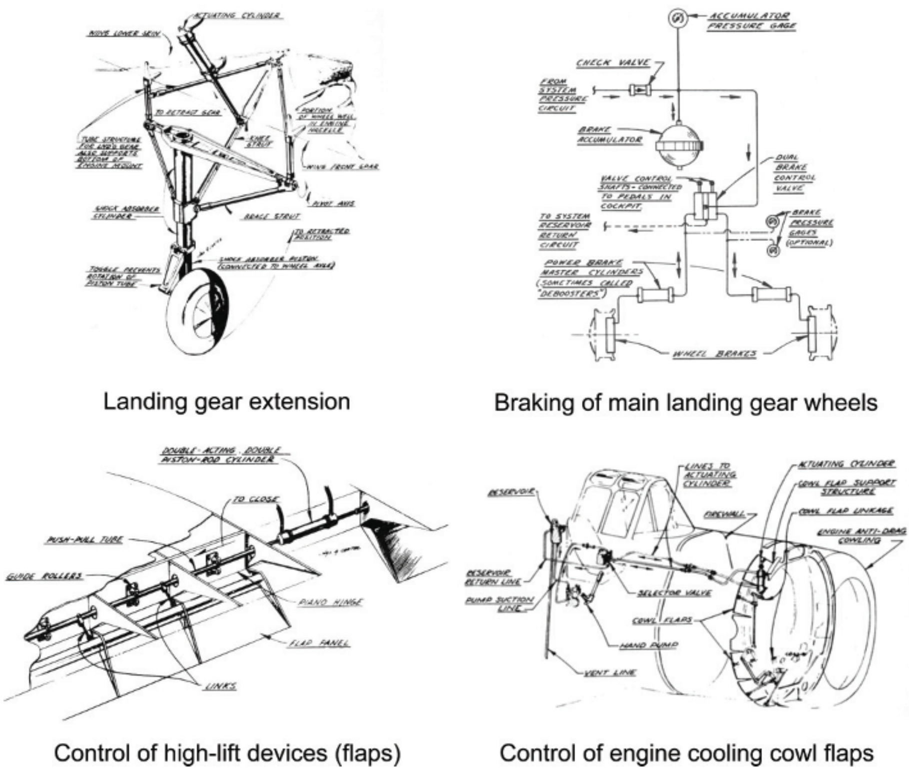
For instance, for an increase in pressure by 100 bar, the hydraulic liquid of a commercial aircraft (ρ= 1,000 kg/m^3 and B = 10,000 bar, in practice) stores a specific deformation energy of 50 J/kg and the relative variation of fluid volume is 1%.

– The four ways of transporting energy using a fluid explicitly appear when they are put together to form the energy equation.

1.3.3. *Historical evolution of power and pressure use*

Increase in power requirements

Hydraulic power implemented in aircraft has been consistently increasing since the dawn of aeronautics. As proven by the many publications on aeronautic hydraulics released between 1937 and 1950, the use of hydraulics first spread to assume transient or pulsed functions. Examples of such functions are shown in Figure 1.7 and they include: extending and retracting landing gear, braking, drawing wing-flaps in and out or even controlling engine cooling cowl flaps.



Landing gear extension

Braking of main landing gear wheels

Control of high-lift devices (flaps)

Control of engine cooling cowl flaps

Figure 1.7. *First applications of hydraulics to aerospace [THO 42]*

Furthermore, in very early days, hydraulics was also implemented to assume continuous autopilot functions. Their purpose was to move control surfaces of primary flight controls by acting on cables or on control linkages in order to maintain a given trajectory in spite of aerodynamic disturbances. The concept of a “gyropilot”, used since the 1920s on boats, was applied by Sperry to aircraft in its three-axis version in the late 1930s. For instance, it was equipped on the Lockheed L-14 as soon as 1937. Figure 1.8 illustrates its operating principle for the roll axis. The detection of undesired roll is performed by a mechanical gyroscope (A) whose rotor is put in rotation by the airflow suctioned from the gyroscope thanks to a vacuum pump (B). In the presence of roll, the gyroscope develops a control command via the rotation of the gimbal ring carrying the rotor. This rotation induces a differential depression on the control membrane (F) of a hydraulic valve (H). The opening of the hydraulic valve meters the amount of hydraulic power transmitted from the pump (J) to the hydraulic cylinder (K) which operates ailerons (M, M’) through cable transmission (L, L’). In manual flight mode, the cylinder chambers are connected via the valve (Z) opening. The cylinder rod slides freely and does not resist to displacements initiated by the pilot. Hence, less than 35 years after the first motorized flight of the Wright brothers, aircraft were already equipped with three-axis autopilots that was purely mechanical, pneumatic and hydraulic.

During the following years, the size and velocities of aircrafts increased considerably. The purely muscular actuation of control surfaces therefore became obsolete because incompatible with the level and duration of effort required of the pilot to operate control surfaces. At first, reversible hydraulic actuators were introduced to carry out assistance functions. They were functionally similar to those used in hydraulic steering assistance for automobiles. However, the limits of reversibility were reached very quickly in the face of flutter issues. This is why hydraulic actuators of primary flight controls became non-reversible. In France, such irreversible servo-controls were developed by Jacottet-Leduc in 1950 who built the first three-axis servo-controlled plane: the Sud-Ouest S0 1021 Espadon. The road was now paved for French supersonic fighter jets. The Jacottet-Leduc irreversible servo-control (see Figure 1.9 and left Figure 1.10) servos the position of the cylinder rod to the position of the control rod. For reliability reasons, it is powered by a double hydraulic power source (main and backup) with constant pressure. In case of loss of power, it switches automatically to direct drive mode, backlash-free, between the control rod and the cylinder rod. The servo-control, which consists essentially of bodies of revolution, is mounted in line with the control linkage of control surfaces. The cylinder is of the differential type and its piston constitutes the body of the hydraulic valve. Power metering between the source and the cylinder is carried out by two hydraulic restrictions whose flow section varies as a function of the lift of balls B_1 and B_2. This ball lifting depends on the cylinder rod position relative to the control rod, which performs the subtracting function of the position servo-loop. Hence, the servo-control performs an assisting function by amplifying the effort provided by the pilot to steer the control surface. The same principle of actuator control by the rod to achieve an "in line" assistance function was applied to the servo-controls of helicopter Alouette III, as shown in Figure 1.10. In this implementation, power metering is carried out by a sharp-edged two-way valve rather than a balls valve.

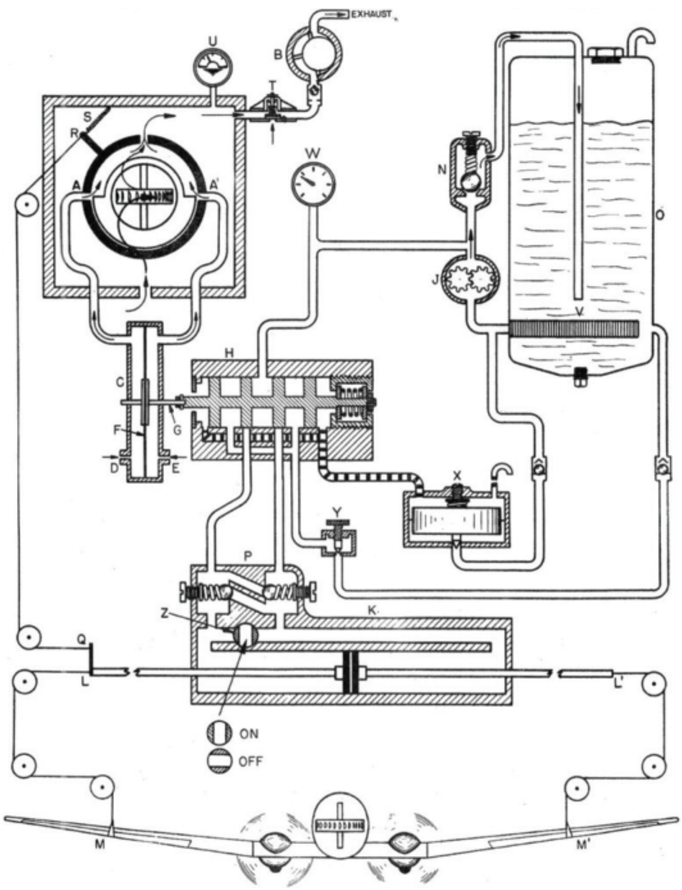


Figure 1.8. *Operating principle of the autopilot in roll [DON 40]*

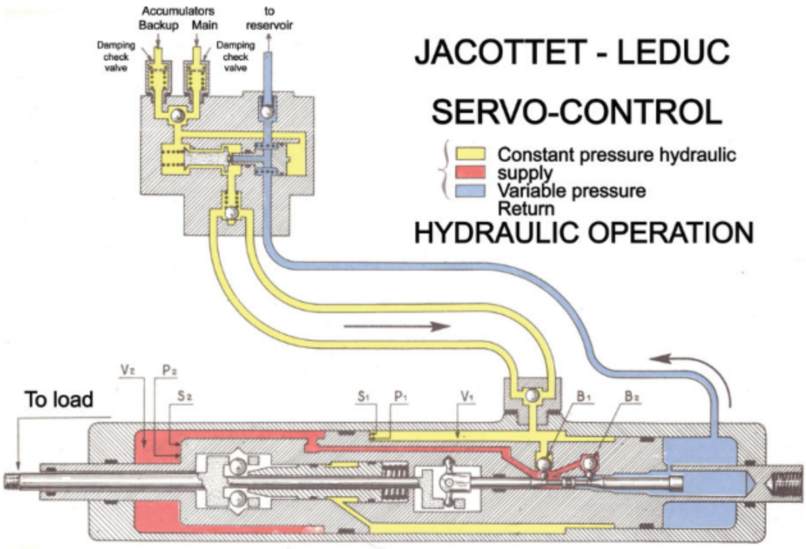


Figure 1.9. *Jacottet-Leduc irreversible servo-control [JAC 54]*

Figure 1.10. *Jacottet-Leduc and Samm hydraulic assistance cylinders (Alouette III)*

The universalization of the use of hydraulics for actuation functions led to a gradual increase of the hydraulic power installed on board: under regular activity mode, a few kilowatts on board the DC3 (1936, 11 tons), 23 kW for the Caravelle (43 tons, 1958), 125 kW on Airbus A320 (1988, 78 tons), 240 kW on Airbus A340 (275 tons, 1993) and 368 kW for Airbus A380 (575 tons, 2007).

This increase in size effect is also well illustrated concerning power requirements for rudder actuation. Stall force and no-load speed are respectively of 3 × 45 kN and 110 mm/s on an Airbus A320, 3 × 94 kN and 135 mm/s on an Airbus A340, 3 × 155 kN and 160 mm/s on an Airbus A340-600 and finally 4 × 225 kN and 100 mm/s on an Airbus A380.

Increase in working pressure

In response to the increase in hydraulic power, while maintaining acceptable mass power and overall dimensions, working pressure has been steadily rising ever since the first use in aeronautics in the 1930s. Indeed, while looking to generate a given force and a given velocity, a raise in pressure enables the displacement of pumps and the section of cylinders to be reduced (see equations [4.1] and [4.2]). And as a consequence, pressure increase also reduces pipe section if the fluid flow velocity is kept constant. On the other hand, it is necessary to increase the thickness of walls, which are required to resist higher hydrostatic stresses. And it is also necessary to further the maturity of sealing and lubrication technologies. In the end, the mass gain mostly shows, in terms of the return lines (and the fluid they contain), that they still operate at the same pressure whereas their diameter can be reduced thanks to the decrease of flow rates that need transmitting.

As shown in Table 1.7, pressure has increased tenfold in a little more than half a century, at the request of spatial and military applications. In the 1980s, serious efforts have been made overseas to assess the benefit of rising the working pressure of military aircrafts to 8,000 psi (552 bar) [JEF 98] [SAE 04]. Knowing the reduction of hydraulic fluid flammability goes hand in hand with this pressure increase, special hydraulic fluids, of type CTFE (chlorotrifluoroethylene), were specially developed [VAN 90]. Compared to the mineral-based fluid Mil-H-83282 commonly used, the combustion heat of fluid CTFE A02 was 7.4 times lower and its auto-ignition temperature was almost double that of the mineral fluid. Unfortunately, its density was increased by 120%, which heavily altered the mass balance. Furthermore, the Bulk modulus was decreased by 11%, which degraded actuator dynamic performance. In the end, the working pressure of fighter jets was frozen at 5,000 psi (350 bar) in the 1990s.

In the early 1960s, the standard working pressure in commercial aeronautics had also been frozen for more than 40 years at 207 bar (3,000 psi). Experience gained in the military and spatial domains made it possible to propagate the pressure increase to commercial transport, albeit with a delay of several years. This delay was in part due to more stringent demands in terms of lifespan, reliability and availability[5]. Since 2007, Airbus with the A380, set a new standard at 350 bar (5,000 psi), which then quickly spread to newer large passenger jets (Boeing 787 in 2011, then Airbus A350 in 2015).

Commercial airplanes	1935 Douglas DC3 35 bar	1959 Caravelle 165 bar	1964 Boeing 727 207 bar	1975 Concorde 280 bar	2007 Airbus A380 350 bar
Military airplanes		1950 Boeing B50 100 bar	1952 Boeing B52 207 bar	1968 Jaguar 280 bar	1991 Dassault Rafale 350 bar
Helicopters	1952 Sikorsky S55 55 bar	1977 Aerospace Super Puma 175 bar	1995 NH industry NH90 207 bar		
Space launchers			Titan 207 bar	1967 Saturn V 250 bar	1996 Ariane V 350 bar

Table 1.7. *Evolution of the working pressure of hydraulic systems in aeronautics*

As a guideline, the weight of hydraulic systems of commercial aircraft typically represents 0.5 to 1.8% [ROS 00] of their maximum take-off weight (MTOW). Regarding the double-deck Airbus A380, it represents 5 tons out of 550 tons and it is estimated[6] that the transition from a working pressure of 207 bar to one of 350 bar made it possible to save between 500 and 1,000 kg out of the overall mass of the hydraulic system.

1.3.4. *Potential advantages and disadvantages of hydraulic technology*

The benefits of transmitting power in hydrostatic form are numerous.

– *High power density of equipment*

For a given piece of equipment (pump or actuator including their power dosing element), the power density can reach 10 kW/kg, in the best case

5 Military airplanes use a hydrocarbon-based fluid whereas commercial airplanes use a synthetic fluid which is more resistant to fire but has restricting properties.

6 The balance of mass consecutive to the increase in pressure is not easy to do because it has many consequences on other systems.

scenario. This is still very high compared to electrical or pneumatic technologies. This advantage is soon dissipated for powers lower than a few kilowatts.

– *Easy generation of large forces at low speed*

Hydraulic cylinders make it possible to generate large forces at low speed in an extremely simple manner. This process involves no other mechanical reducer than a lever arm effect provided directly by the driven load: this is commonly called a direct drive design.

– *High dynamic response characteristics and high acceleration abilities*

In the absence of a high reduction gear ratio, inertia (mass or moment of inertia) of the moving parts of the actuator reflected at the load is in general very weak with regard to inertia of the load to be moved. As a consequence, during transient phases, hydrostatic forces are predominantly transmitted to the load and are not spent to accelerate moving parts of the actuator itself.

– *Easy dissipation of heat generated by energy losses*

Hydraulic fluid is a very good heat transfer fluid. At the component output, it “naturally” extracts heat generated by energy losses caused within the component. In that regard, power transmission via material transport (hydraulic fluid) is an advantage.

– *Easy implementation of secondary functions*

Hydromechanical power transformers, such as cylinders, show excellent mechanical efficiency and weak mechanical inertia. Pressure in the actuator is therefore an accurate representative of transmitted force, even in transient phases. Therefore, secondary functions such as de-clutching, protecting against excess force or even damping at end-stop, can be performed in the hydraulic domain with low weight, small overall dimensions and high reliability.

– *Absence of sensitivity to (or generation of) electromagnetic interferences*

Electromagnetic interferences have no impact on the behavior of hydromechanics. Hydromechanical components do not generate electromagnetic interferences.

– *High technological maturity*

Technological solutions implemented to transmit and dose power have been established for several decades[7] already. Based on the experience feedback collected for years, databases, standards and recommendations have made it possible to master risks over the entire lifecycle of components and systems.

As always, benefits are counterbalanced by a number of drawbacks, some of which are less and less tolerated:

– *Low power density of the distribution*

Supply and return hydraulic lines, as well as the fluid they contain must be able to resist pressure, external impacts and vibrations. Their weight significantly impacts the global power density of hydraulic systems, more strongly so in large aircrafts that may comprise several kilometers of hydraulic lines. Two examples help illustrate this drawback. The first concerns Airbus A380. For this type of very large aircraft, it appears that the weight of hydraulic equipment typically constitutes 25% of the total weight of the hydraulic system. Pipes, clamping and hydraulic fluid account for the remaining weight. The second example deals with Boeing B777. The main hydraulic pump of the Boeing delivers 182 l/min at a working pressure of 207 bar and has a dry mass of 18.2 kg. In order to transmit this power, several meters of pipes are required. One meter of supply and return pipes typically weight 1.5 kg including the fluid they contain (low pressure pipes made of aluminum and high pressure made of titanium, average fluid speed 7 m/s). Hence, 12 m of lines, sized to allow the transmission of all the power supplied by the pump, weight, with their fluid, the same as the (dry) pump itself!

– *Fluid conditioning requirements*

The hydraulic fluid must be conditioned. Additionally, any assembly or maintenance task imposes harsh constraints regarding security, pressurization, pollution, bleeding and leakage collecting.

7 However, this does not mean that there is no room for improvement!

– *Difficult power management and low re-configurability*

The cost of reducing risks of propagation of fluid pollution and leakage translates into severe requirements that impose independent and segregated redundant hydraulic systems. This considerably hinders power management and limits reconfiguration possibilities for power networks.

– *Integration restrictions*

Bending radii of hydraulic lines are limited by the concentration of mechanical stresses they generate. Moreover, the tolerance for accidental leakage forces the minimization of fire hazard in the vicinity of hot parts (engines) as well as spraying hazard in the cabin. These restrictions have to be added to the previously discussed independence and segregation requirements. In the end, those constraints heavily impact the routing of hydraulic networks and the location of equipment.

– *Aggressiveness of the hydraulic liquid*

Hydraulic liquids, in particular those used in commercial aviation, are skin and eye irritants. They attack numerous different materials and pollute the environment. This aggressiveness is a strong argument to the detriment of hydraulics.

– *Power metering by energy dissipation*

Metering of the amount of power transmitted to driven loads is, in the vast majority, carried out by power dissipation through hydraulic valves. Power is therefore consumed as if generating full force, regardless of the effort requested by the load.

– *Permanent internal leakage*

In order to ensure the smooth and accurate operation of hydraulic equipment, it is necessary to tolerate permanent internal leakage, for example, to implement dynamic sealing or at servovalve pilot stages.

Finally, in comparison to other technologies, the benefits still very clearly outweigh the disadvantages of hydraulic technology. However, the lightning-speed development of electrical technologies (power electronics, electric machines, controls) has already led to successful flight-worthy developments, although only with the purpose of partially performing critical actuation functions (for instance for the actuation of 4 out of the 14 spoilers on Boeing B787). It is difficult to accurately compare technologies because it requires assessing the gain for the final user, for example, the passenger and the airline company. To carry out this comparison process fairly, it is important to remember not to conceal intrinsic benefits of "conventional" solutions and to research in depth drawbacks specific to "newer" solutions. Goals and restrictions should also be considered from a global, lifecycle point of view, regarding new services that can be provided as well as risk, costs and environmental impact minimization.

1.3.5. *Overall hydraulic circuit architecture*

Figure 1.11 shows a hypothetical power architecture of an aerospace hydraulic system. Without going into details, the first step is to visualize the architectural concepts applied to carry out the most generic functions of hydraulic power transmission, which are:

– convert power between the hydraulic and mechanical domains;

– transport hydrostatic power using properly conditioned hydraulic fluid;

– dose the power transmitted to the load;

– manage (distribute/transmit) power as a function of life stages, reliability constraints and response to failure.

These four major functions will each be addressed in one of the following chapters of this volume. A final chapter is dedicated to the integration of components, equipment and hydraulic systems.

As shown on Figure 1.11, hydraulic schematics that will be introduced in this book will respect as much as possible standard symbols SAE-AS1290-B [SAE 11]. Additionally, colors will be used to differentiate high pressure lines (red), low pressure lines (dark blue), suction (light blue) and actuators (green).

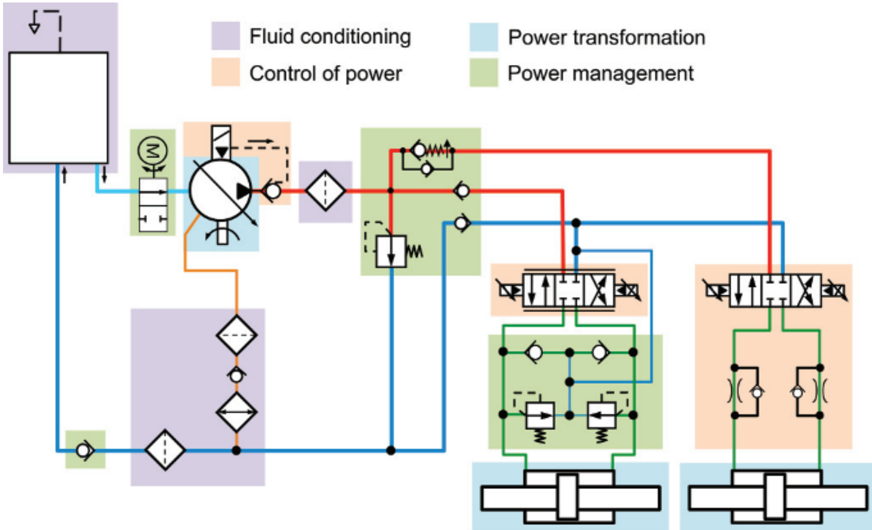


Figure 1.11. *Typical hydraulic system architecture. For a color version of the figure, see www.iste.co.uk/mare/aerospace1.zip*