THE HONG KONG POLYTECHNIC UNIVERSITY
香港理工大學

Department of Aeronautical and Aviation Engineering
航空及民航工程學系

Introduction to Aircraft Systems

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Notice for March 7th lecture

- According to the schedule, we will have an in-class quiz next week.

	Date	Content		Assignment
1)	17-Jan-25	• Overview		
2)	24-Jan-25	• Aircraft Control Systems		
3)	07-Feb-25	• Aircraft Landing Gear Systems	Assignment 1	
4)	14-Feb-25	• Aircraft Engine System		DDL for Assignment 1
5)	21-Feb-25	• Aircraft Fuel Systems		
6)	28-Feb-25	• Aircraft Hydraulic Systems	Assignment 2	
7)	07-Mar-25	• Aircraft Electric Systems • In-Class Quiz (closed book)		DDL for Assignment 2
8)	14-Mar-25	• Atmospheric Conditions	Course Project	
9)	21-Mar-25	• Aircraft Pneumatic Systems • Aircraft Environmental Control System	Assignment 3	
10）	28-Mar-25	• Aircraft Environmental Control System • Aircraft Emergency System		DDL for Assignment 3
11）	04-Apr-25	• Public holiday		
12）	11-Apr-25	• Reserved for guest lectures/Avionics systems		
13）	18-Apr-25	• Public holiday		DDL for Course Project

- We will have an 15-min AIESEC briefing

AIESEC would like to hold a briefing session with AAE undergraduate students to share some exciting opportunities for them to gain international exposure and develop valuable skills. We would like to know if you could spare 15 minutes during your lecture time for this briefing.

Please let me know if there is any objections and I will let them know.

Aircraft hydraulic system/液壓系統

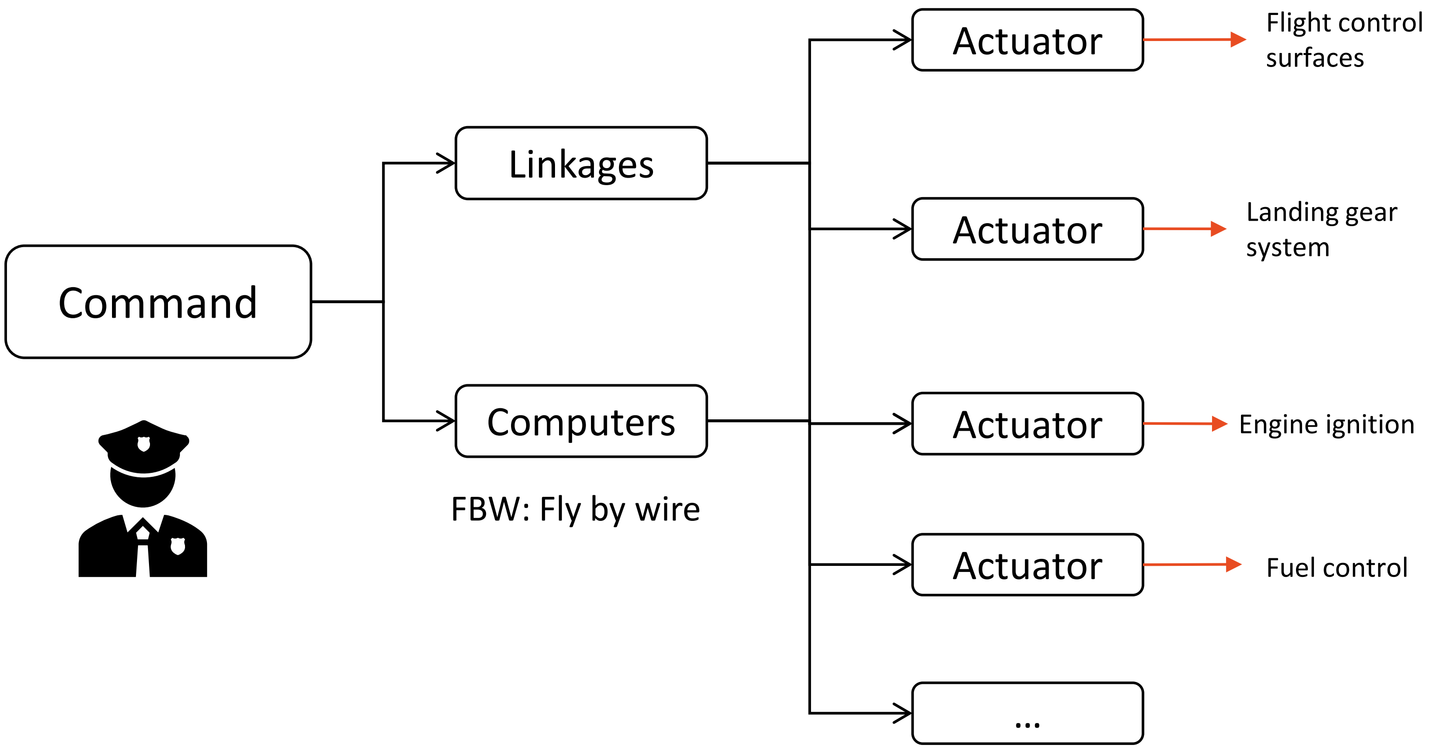
- Introduction
- Basis of hydraulic systems: hydrostatics
- Hydraulic system components
  - Actuator, Reservoir, piping, valves, pumps
  - Hydraulic Fluids, Pressure & Temperature
- Power distribution
- Summary

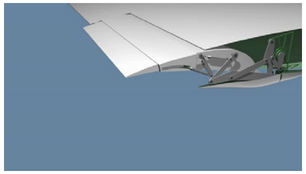
Douglas DC-3 had wing flaps powered by hydraulics, 1934

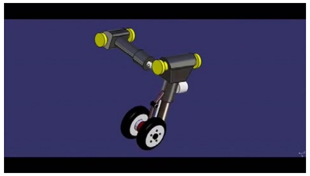
Introduction

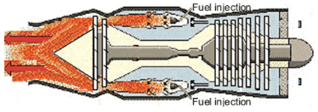
Introduction

- In aircraft control systems, landing gear systems, and other systems, command from the pilot are made, transferred to the target components through linkage systems. To realize the control effect, sufficient actuations should be provided to response to the command.









Introduction

- In industry, there are several major methods to transmit the power from one point to the other:
  - Mechanical: through shafts, fears, chains, cables, etc.
  - Electrical transmission: wires, rectifiers, etc.
  - Fluid power: through liquids or gas in a confined space

With the increasing complexity, weight and speed of the aircraft, it is impossible all actions are realized through the power of the pilot mechanically.

We will introduce this part in the “Electrical system” part.

Introduction

- Fluid contains gas and liquid
- Fluid power: to use pressurized fluid to transfer power/energy
  - Hydraulic system/液壓系統: to use pressurized liquid such as *water* or *oil* to transfer power from one point to another
  - Pneumatic system/氣壓系統: to use pressurized gas such as air or other gases to transfer power from one point to another

What are pressurized liquid and gas?

Hydraulic power

- Hydraulic power appeared as an efficient way to transfer power from small energy movements in the cockpit to high energy demands in the aircraft.
- Terminology:
  - Greek words: hudro (Water) + aulos (pipe) → hudraulikos
  - Latin: hudraulikos (Greek) → hydraulic (Latin). In early 17th century
- In the hydraulic system, the fluids are incompressible.

Compressibility is a measure of the relative volume change of a substance being subjected to pressure.

A difference between the two fluid types, i.e., liquid & gas, is that: gas is easier to be compressed while liquid is nearly incompressible.

Application of hydraulics in aircraft

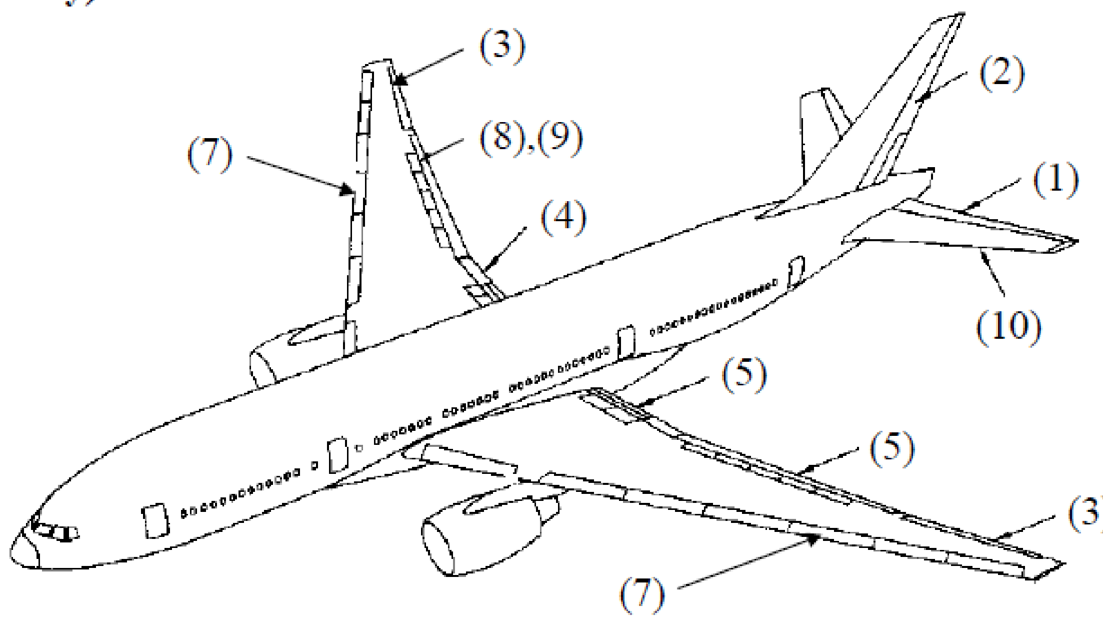
- The widespread use of hydraulics in aircraft started during **World War II** when significant advances in aircraft hydraulic technology were made.
- By the 1960s, hydraulic systems had become standardized in commercial and military aircraft, providing reliable performance and safety.
  - Aircraft like the Boeing 747, introduced in 1968, featured a centralized hydraulic system.

Application of hydraulics in aircraft

- In aircraft, the hydraulic systems are widely used to **transfer power** to *operate* or *move* components within a closed loop system:
  - Effective
  - Reliable
  - Low weight-to-power ratio
  - Responsive
- Hydraulic systems are especially important for the safety-critical systems

Hydraulic system load

- **Primary Flight Controls:**
  - **-Elevators – (1)**
  - **-All-moving tail surfaces (military)**
  - **-Rudders – (2)**
  - **-Ailerons – (3)**
  - **-Flaperons – (4)**
  - **-Canards**
- **Secondary Flight Controls**
  - **-Flaps – (5)**
  - **-Slats – (7)**
  - **-Spoilers – (8)**
  - **-Airbrakes – (9)**
  - **-Stabilizer trim – (10)**
- **Utilities**
  - **-Landing gear**
  - **-Brakes**
  - **-Gear steering**
  - **-Aerial refueling probes (military)**
  - **-Cargo doors**
  - **-Loading ramp (military)**
  - **-Passenger stairs**

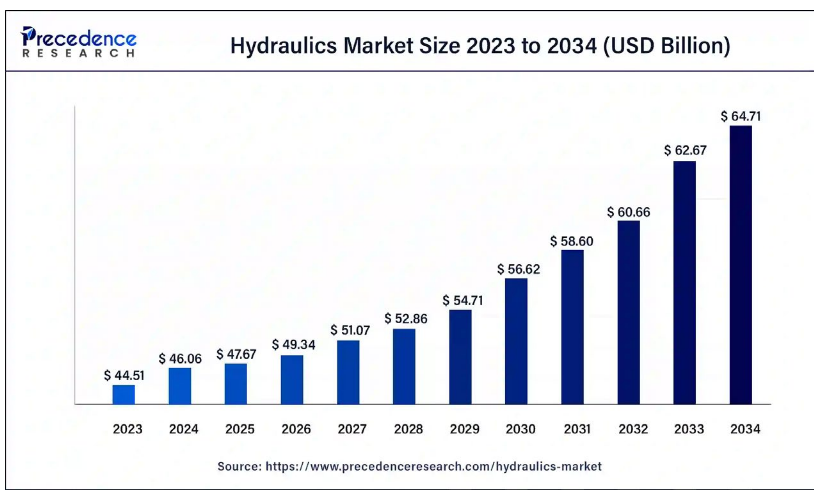


Hydraulic systems V.S. electric systems

- It becomes apparent that in some areas the hydraulically-powered systems are replaced by electric systems.
  - Hydraulic systems still have advantages in low weight per unit power
- Factors to consider when selecting different power systems:
  - Low weight
  - Low volume
  - Low initial cost
  - High reliability
  - Low maintenance cost, etc.

Aircraft hydraulic system

- Major aircraft hydraulic system companies include:
  - Raytheon Technologies Corporation (U.S.)
  - Parker-Hannifin Corporation (U.S.)
  - Safran S.A. (France)
  - Eaton Corporation Plc (Ireland)
  - Liebherr-International Deutschland GmbH (Switzerland)



Basis: hydrostatics /流體靜力學

Hydrostatics/流體靜力學

- A hydrostatics system uses fluid pressure to transmit power
  - It generates high pressure, which drives the motion of an object, which could be linear or rotational, through a transmission line
- Properties of the hydrostatic transmission:
  - Small flow rate
  - Large pressure

Statics: so we can apply hydrostatics for analysis & design

Ensure the ability of driving motions

Hydrostatic pressure

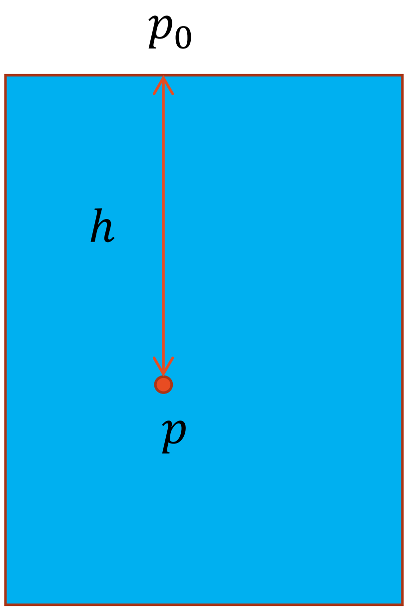
- The pressure at a point in a static liquid depends only on the depth:

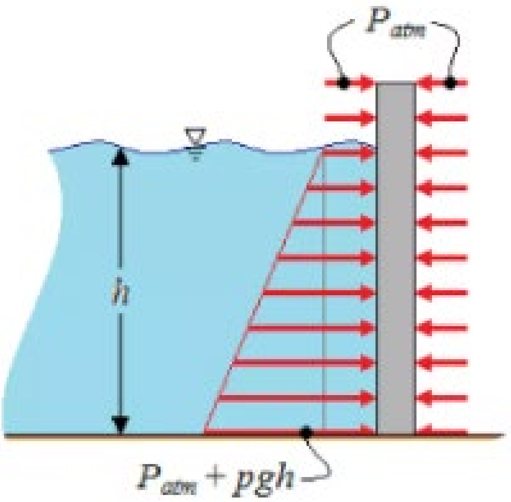
$$p = p_0 + \rho g h$$

Here the variables are:

- p: pressure at the point
- p_0: external pressure/reference pressure at the surface
- ρ: liquid density
- g: gravity acceleration
- h: depth

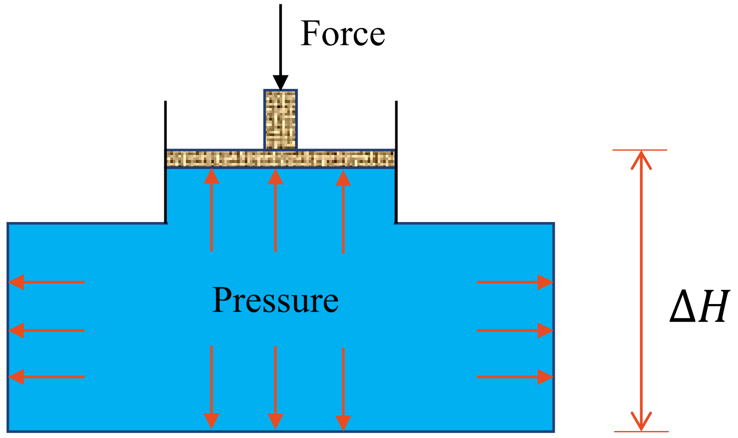
- The hydrostatic pressure increases with the depth, explaining why the water dams are built with trapezoidal shapes.





Pascal's principle

- When the height difference is negligible, any change in the pressure applied to a completely enclosed fluid is transmitted equally in all directions and walls without any loss.
- The law was discovered by the French scientist Pascal in 17th century.



Blaise Pascal (1623-1662),
French scientist & philosopher

The pressure difference is

$$\Delta p = \rho g \Delta H$$

If ΔH is small, then the pressure difference is small

Pascal's principle

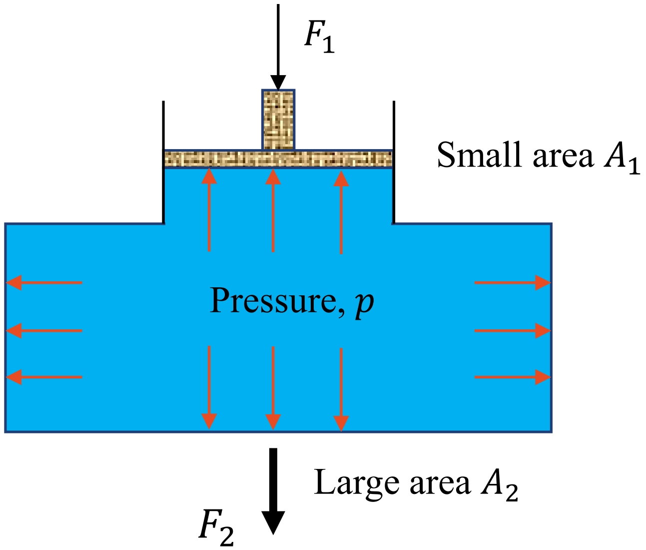
- By definition, the pressure is:

$$p = \frac{F_1}{A_1}$$

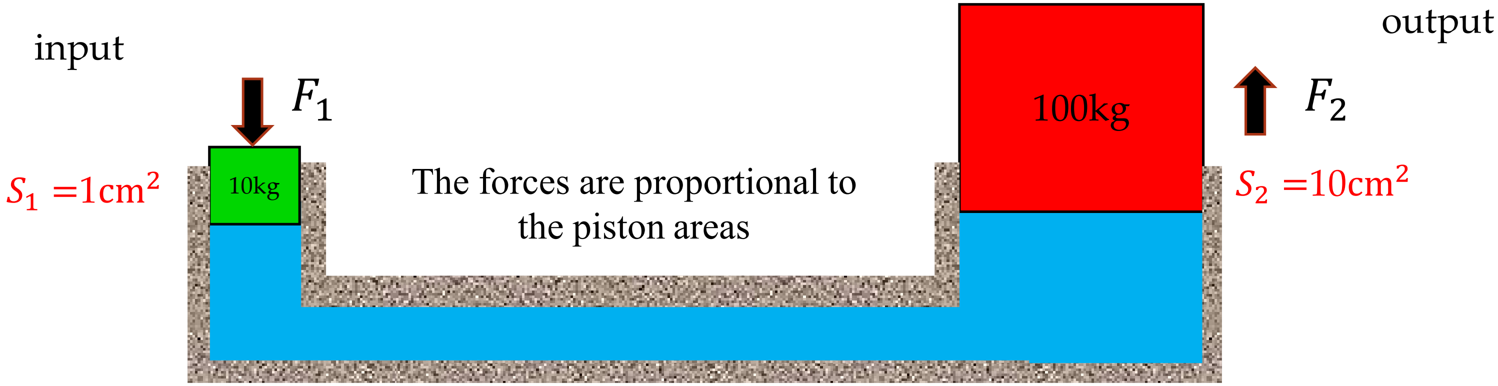
- Using Pascal's law, the force acts on the bottom is

$$F_2 = pA_2 = F_1 \frac{A_2}{A_1}$$

- The magnitude of force transmitted is directly proportional to the surface area ratio!

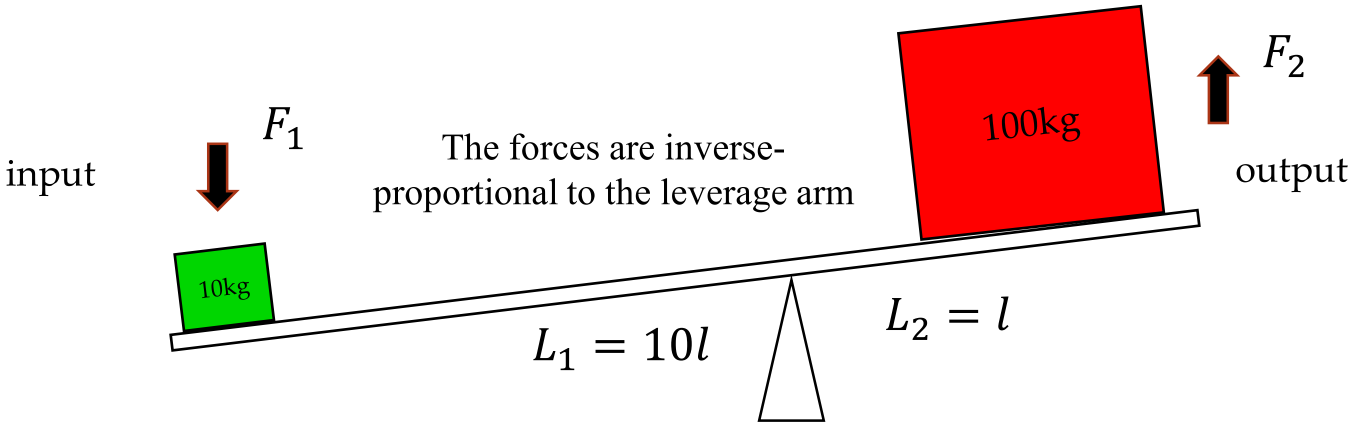


Application example: hydraulic leverage



hydraulic leverage

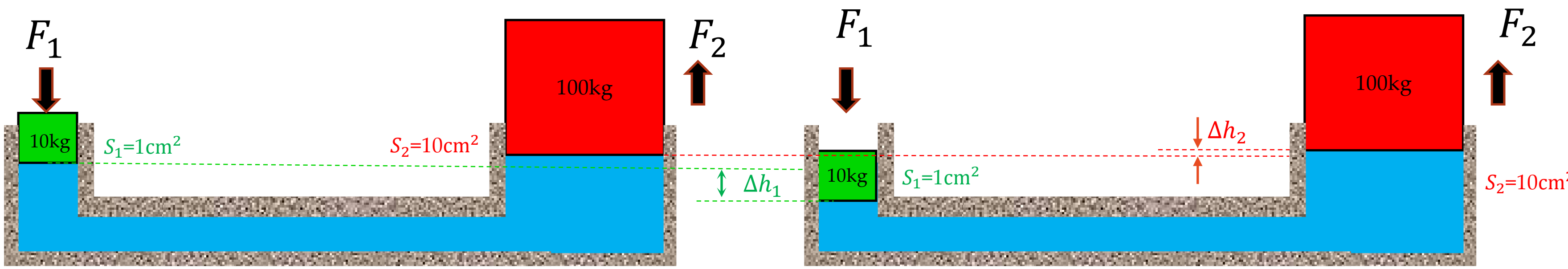
Comparison: mechanical leverage



$$F_1 \cdot L_1 = F_2 \cdot L_2$$
$$\Rightarrow L_1 = L_2 \left(\frac{F_2}{F_1}\right)$$

- If we want to achieve a displacement of the heavier object, we will need a much longer displacement for the input force.
  - The displacement is in the opposite direction. This will lead to a large space usage!
  - The speed of the input end will be propositionally increased!

Property in a hydraulic leverage



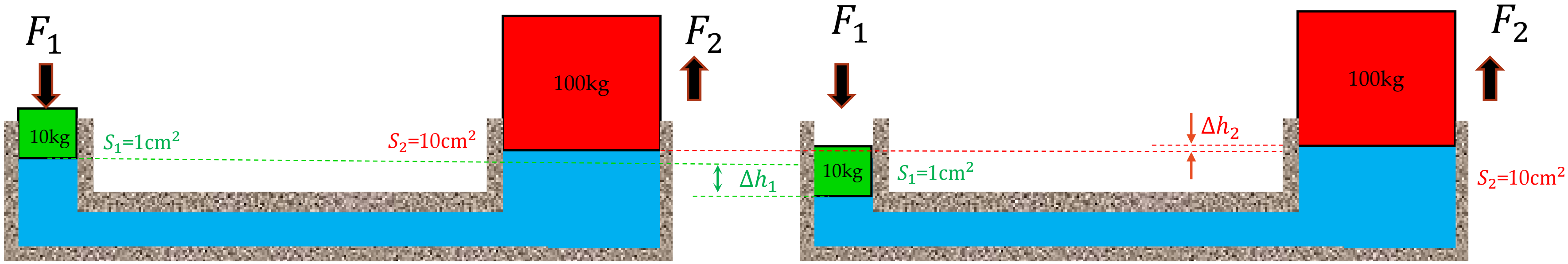
- From mass conservation:

$$\cancel{\rho} S_1 \Delta h_1 = \cancel{\rho} S_2 \Delta h_2$$

$$\Delta h_1 = \Delta h_2 \cdot \left(\frac{S_2}{S_1}\right) = \Delta h_2 \cdot \left(\frac{S_2 \cdot p}{S_1 \cdot p}\right) = \Delta h_2 \left(\frac{F_2}{F_1}\right)$$

- There will be a longer distance in Δh_1 if the force ratio is high
- However, this distance/displacement is not restricted to a particular direction. Instead, it can be curved.
- Then, we can use pipes to provide the given Δh_1. Space will be saved!

Property in a hydraulic leverage



- The work at input

$$W_1 = F_1 \Delta h_1$$

- The work output is

$$W_2 = F_2 \Delta h_2 = pS_2 \Delta h_2 = \frac{F_1}{S_1} S_2 \left(\frac{S_1}{S_2} \Delta h_1 \right) = F_1 \Delta h_1 = W_1$$

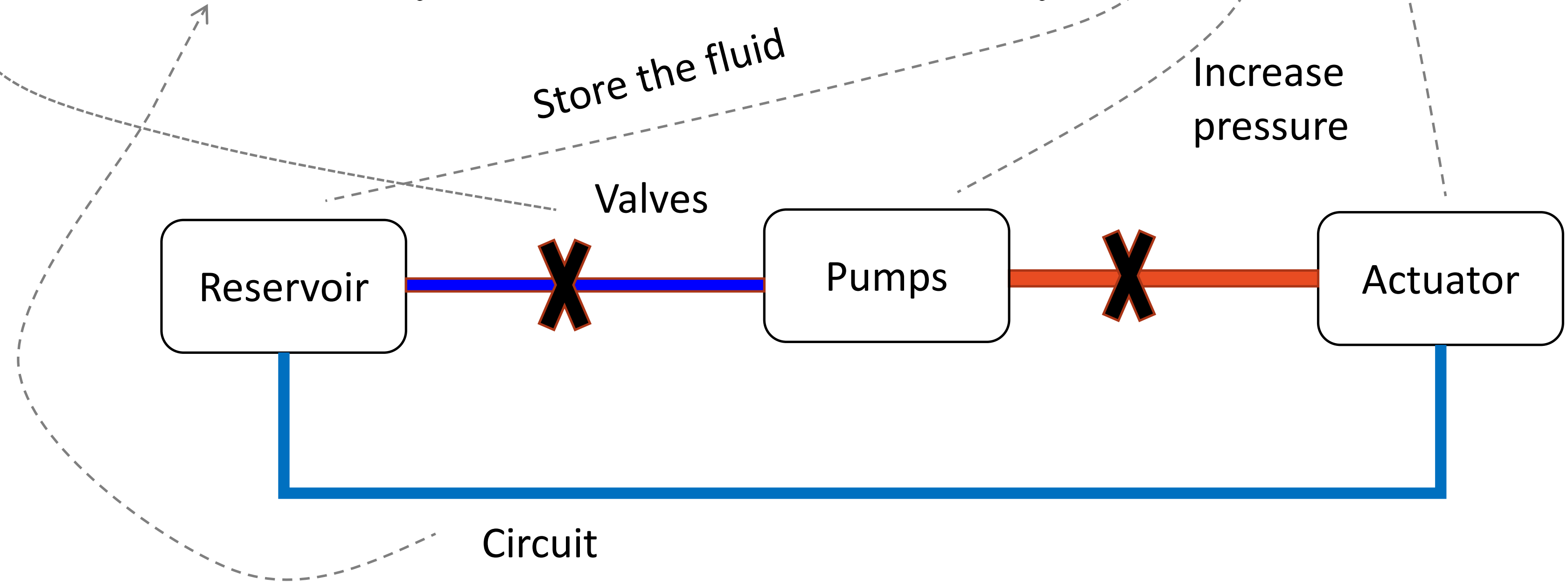
- Energy cannot be created or destroyed. We must do the same amount of work to leverage the heavier object.

Hydraulic system design

Hydraulic system design

What is the fluid to be used?

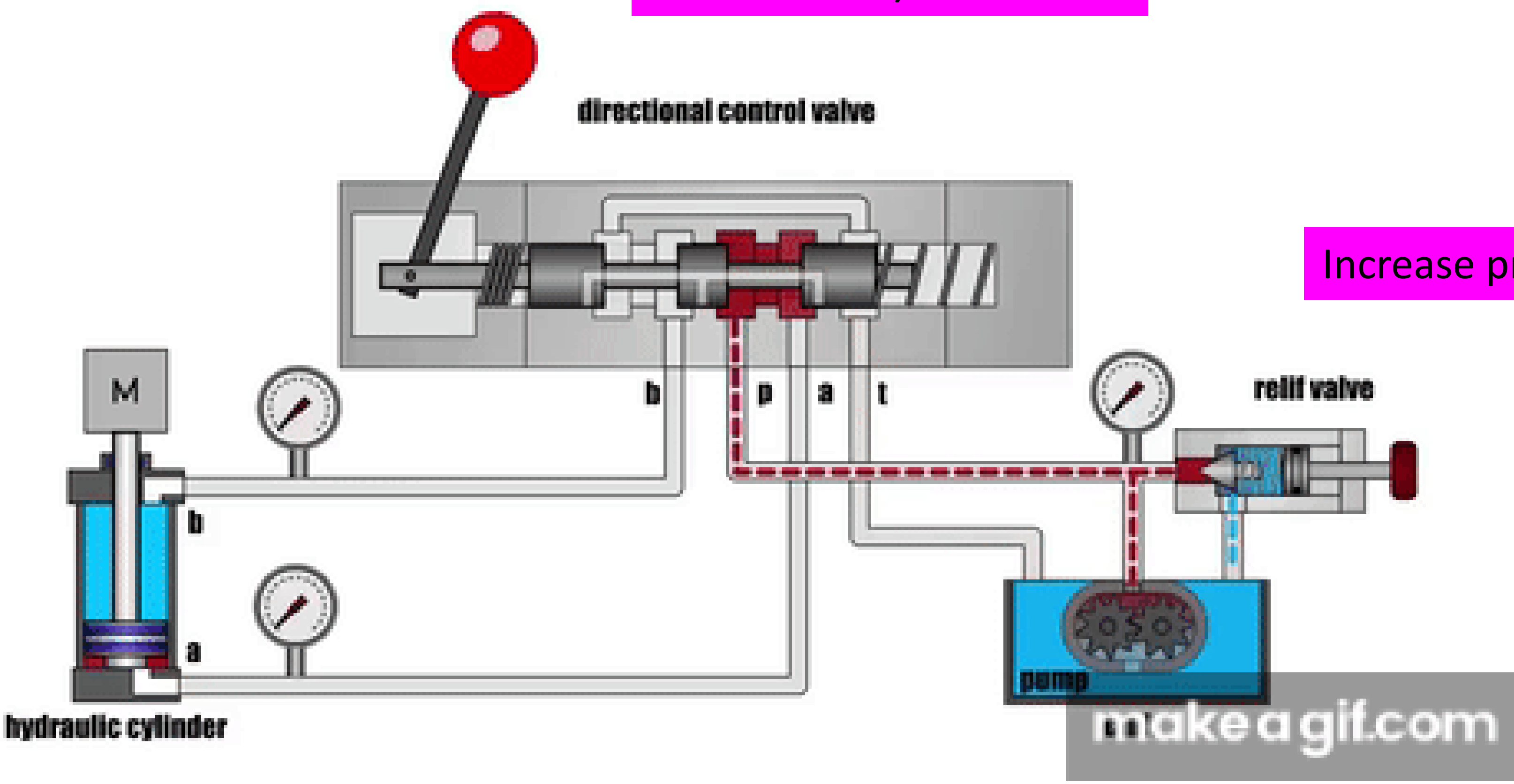
- For aircraft application, we need to address:
  - How the pressurized fluid is used?
  - How the pressurized fluid is achieved?
  - How the pressurized fluid is provided?
  - How the pressurized fluid is controlled?
  - How does the system work in a sustainable way?



Working principle of hydraulic system

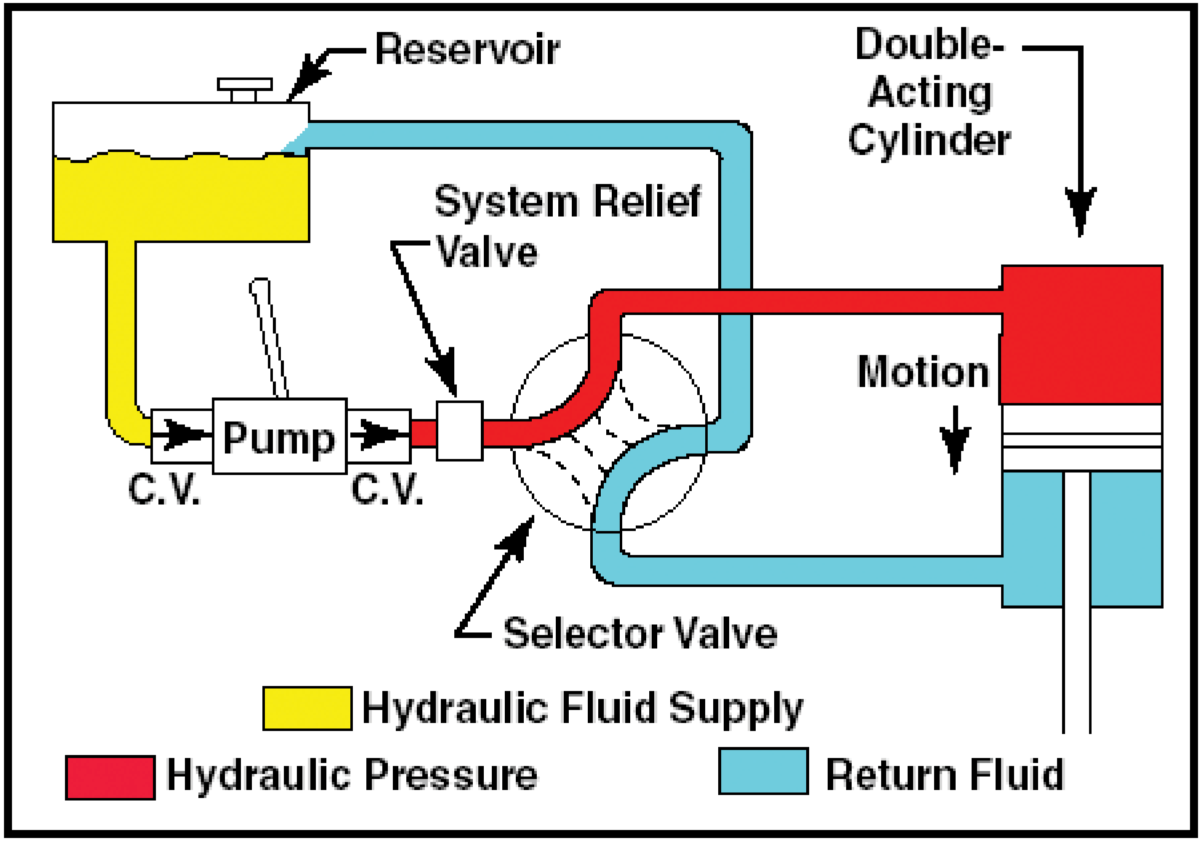
Control the hydraulic fluid

Increase pressure



Actuator

Working principle of hydraulic system



Hydraulic system design

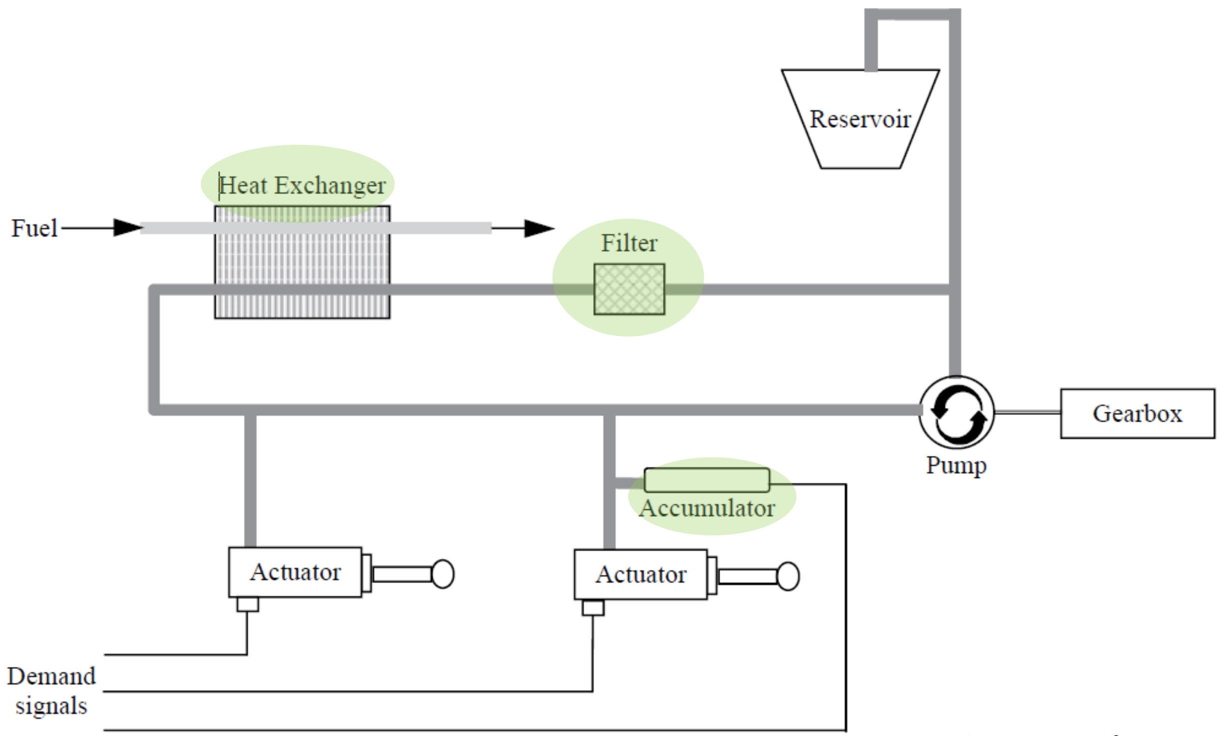
- In practice, the design will be more complicated because several other issues should be considered:
  - What the flow rate demanded for angular or linear motion?
  - What is pressure of the system?

    Fundamental function
  - Is the system heat loaded or dissipated?

    Performance
  - Is the system flight safety critical or tolerable?
  - Is there a need of power source under emergency?

    Safety & reliability
  - …

Schematic of a simple hydraulic system



In practice, to achieve the levels of safety, at least two or more hydraulic circuits are needed. Here we only introduce the functionality of the major components in this circuit.

Hydraulic system design

- Analysis of these factors leads to the following components needs:
  - A means for exercising demand: actuators, motors, pumps, etc.
  - A source of energy: engine, auxiliary power, etc.
  - A reservoir to store the fluids
  - Multiple redundant distribution systems: pipes, valves.
  - A filter to ensure clean fluid
  - A mechanisms for cooling: heat exchanger
  - A means of storing energy: accumulator
  - Temperature and pressure sensors
  - …

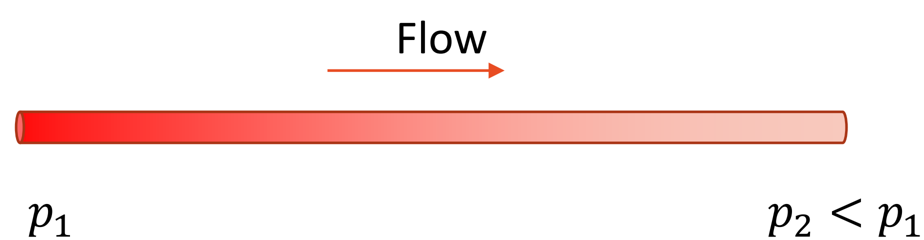
Hydraulic system design

- In this lecture, we are going to introduce the following elements briefly:
  - Hydraulic fluid
  - Hydraulic actuation
  - Hydraulic fluid pressure
  - Hydraulic fluid temperature & heat exchanger
  - Hydraulic fluid flow rate & accumulator
  - Hydraulic reservoir
  - Hydraulic pipelines
  - Hydraulic pumps
  - Hydraulic filters

1. Hydraulic fluid

- The hydraulic fluid is the medium used to transmit the power.
- General requirements for them includes the **maximum temperature** and **maximum flow rate**.
- The mineral based fluid are commonly used, e.g.:
  - UK: DTD 585
  - US: MIL-H-5606
  - France: AIR 320
  - China: YH-10(10號航空液壓油)

- Pros and cons of the mineral based fluid:
  - Cheap and the viscosity is insensitive to the temperature
  - They are flammable and the limited working temperature is below 130°C

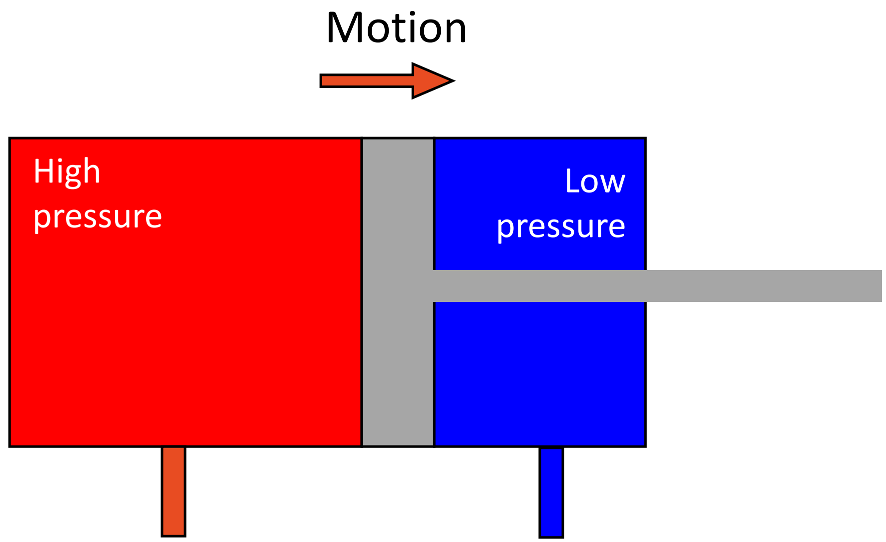


1. Hydraulic fluid

- To reduce the flammability, some new hydraulic fluids were into service, e.g.:
  - MIL-H-83282 is a entirely synthetic fluids
- The fluids are not fireproof and there are possibilities they will burn:
  - Standardized tests should be conducted to ensure the possibility of the hydraulic system design encounter fire and burn is within the acceptable level.

2. Hydraulic actuation

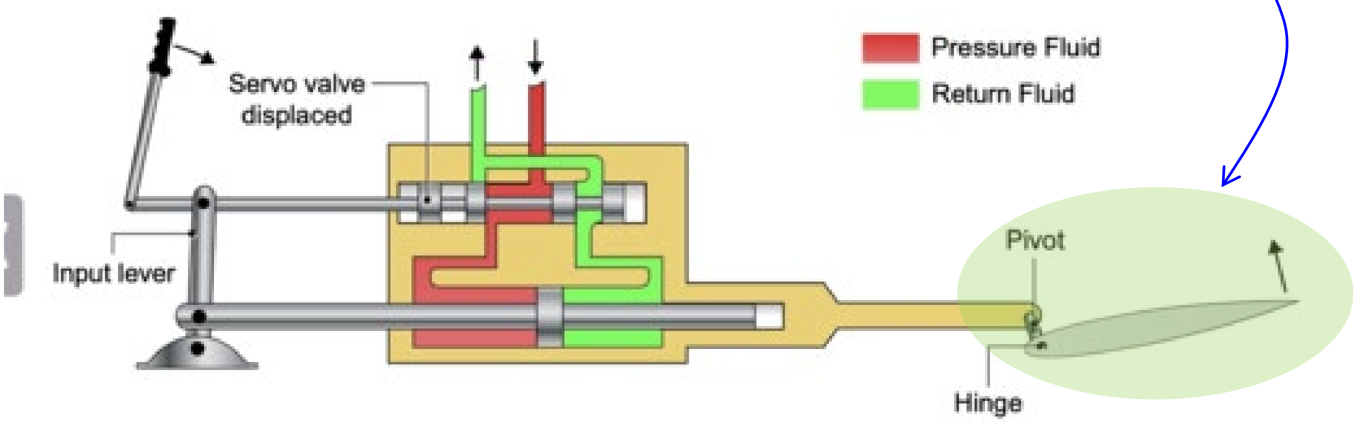
- The hydraulic system is used to acts as an actuator for the control purposes
- The actuation is provided by the motion of the piston, the motion of which is driven by the pressure of the fluids.



A simplified model for motion provided by hydraulic pressures. But the actual situation is much more complicated.

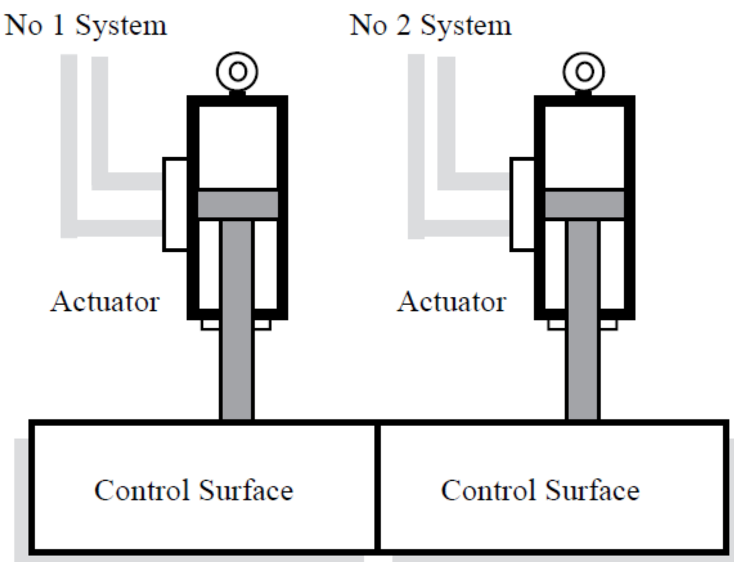
2. Hydraulic actuation

- In practice, structure of the actual hydraulic actuator can be more complex.
- Here we take the flight control surface for example.



2. Hydraulic actuation

- Each control surface is split into two or more independent parts and each parts has its own actuator
- A common actuator for the primary flight control consists two pistons in tandem (see next page).
  - Each piston is connected to a hydraulic system.



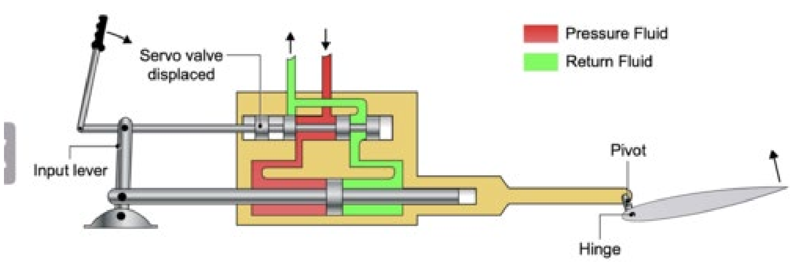
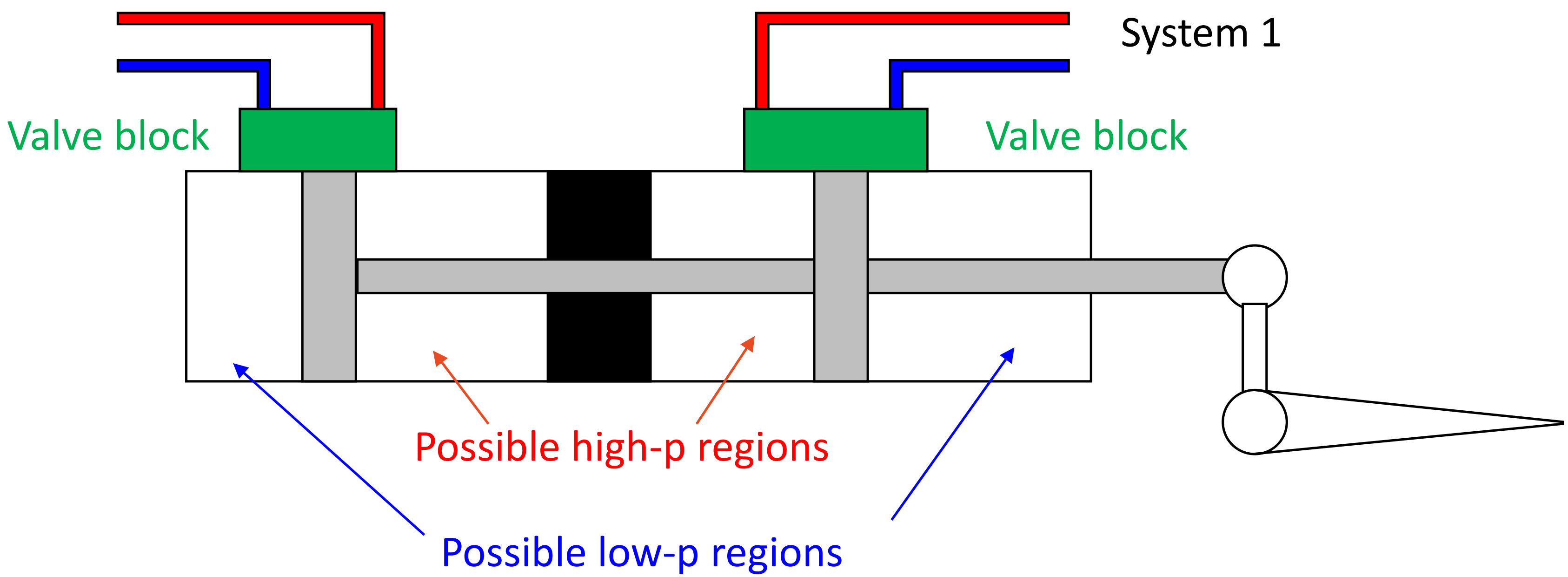


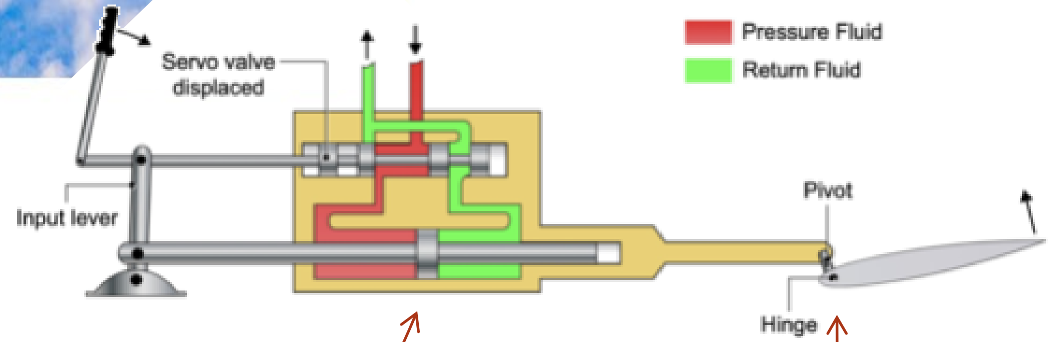
Figure 8.6 Power assisted flying controls

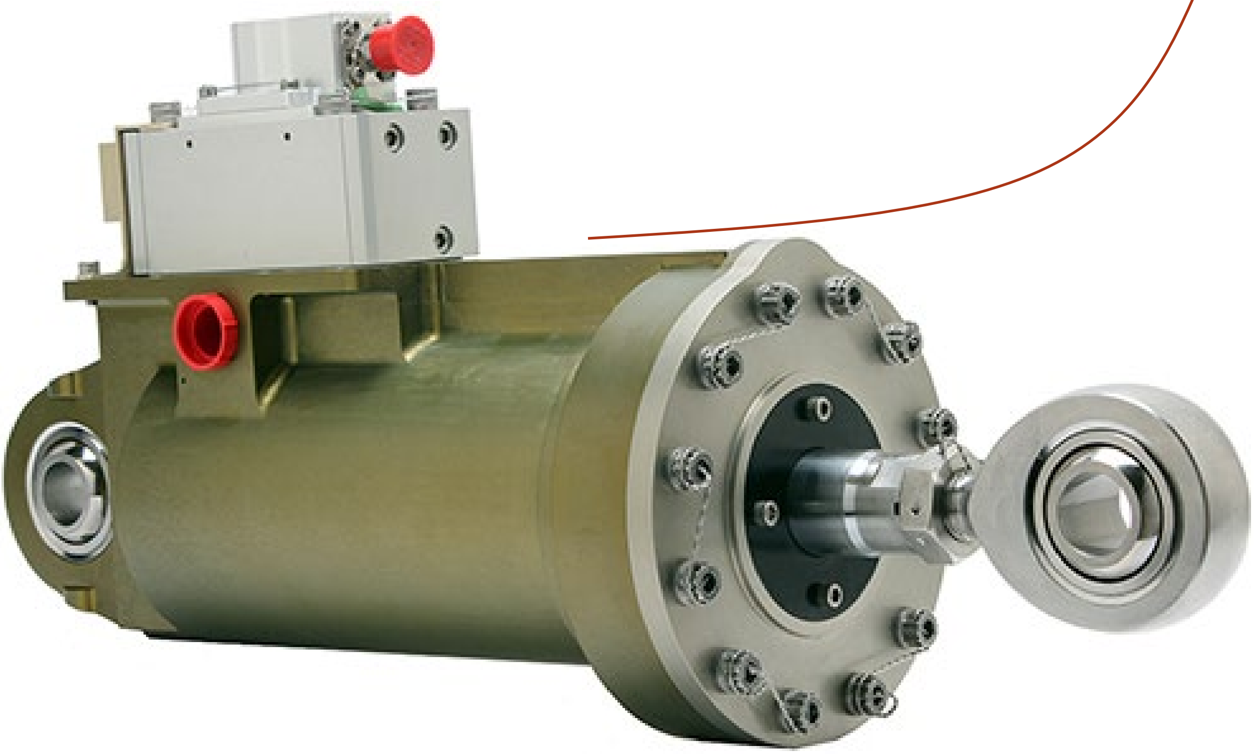
2. Hydraulic actuation

- In most time, the actuators remain in a quiescent as they often move slowly.
- They are commended to different states by mechanical or electrical devices. Therefore, the actuators also include the valves to allow the hydraulic fluid move in either direction.



2. Hydraulic actuation





JASC 101413 Hydraulic Servo-Actuator

1 pound per square inch (psi)=6895 Pascal

3: Hydraulic fluid pressure

- Performance of the hydraulic system is affected by the working pressure.
- Typical range of the working pressure is about 3000psi.
  - They have been chosen to keep weight of the hydraulic system to a minimum
- There are efforts trying to improve the working pressure. However, in practice, the optimal pressure will depend on the aircraft design.

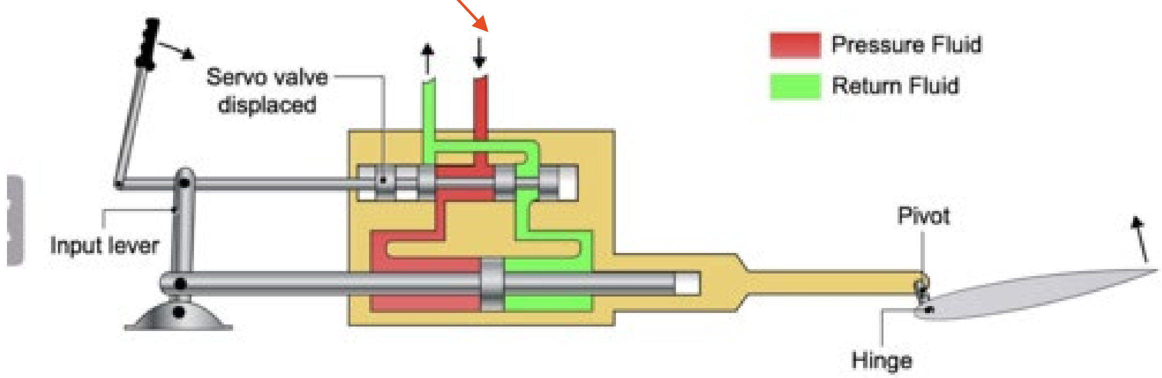


Figure 8.6 Power assisted flying controls

4: Hydraulic fluid temperature & heat exchanger

- Temperature of the fluids can be high in the aircraft systems:
- However, high temperature can affect the hydraulic system:
  - The hydraulic oils have limited working temperature
  - The viscosity is reduced and might cause damages
  - Some oils (e.g., phosphate ester based ones) can be degraded as hydrolysis/水解 and oxidations/氧化
- Thus, heat exchangers are often needed to ensure the hydraulic system is operated at proper temperature

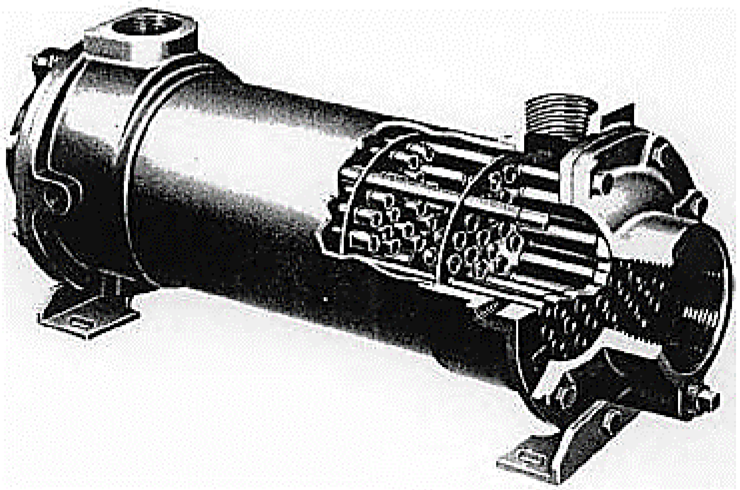


FIGURE 8.1
Shell-and-tube exchanger used to cool hydraulic oil. (Courtesy of Honeywell, Corona, CA.)

5: Hydraulic fluid flow rate & accumulator

- The hydrostatics suggests the flow is in the quiescent state. However, the motion of the actuator and the piston actually involves speeds.
  - Friction, geometry and speed
  - The actual pressure will be lower than the nominal pressure (20~25%)

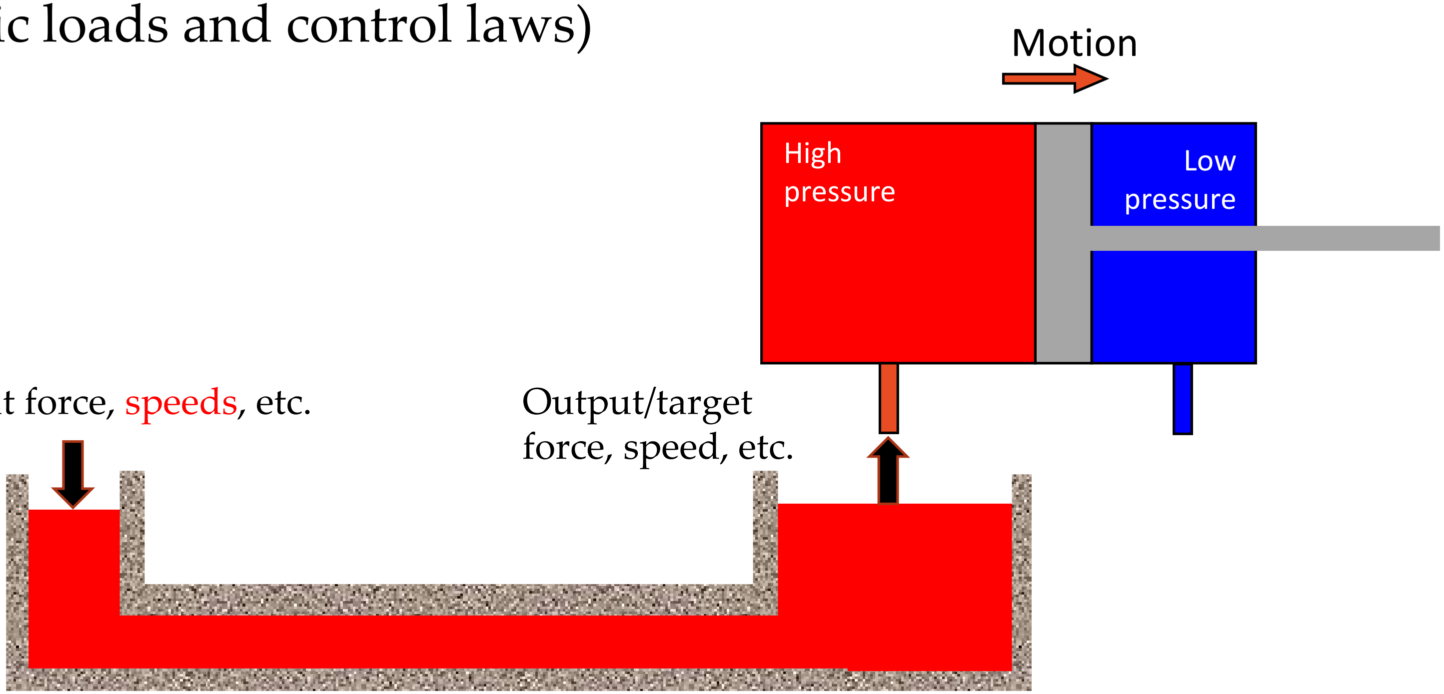
To understand this, we use the Bernoulli equation:

$$p + \frac{1}{2}\rho V^2 = \text{const.}$$

With the increase of V, which is ignored, the pressure will be dropped.

5: Hydraulic fluid flow rate & accumulator

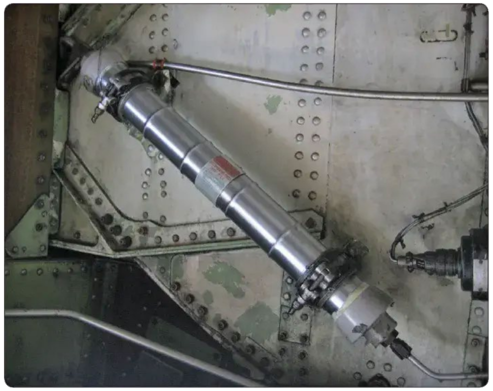
- In the design phase, the piston area and flow rate should be considered in combination with the target loading (based on the aerodynamic loads and control laws)

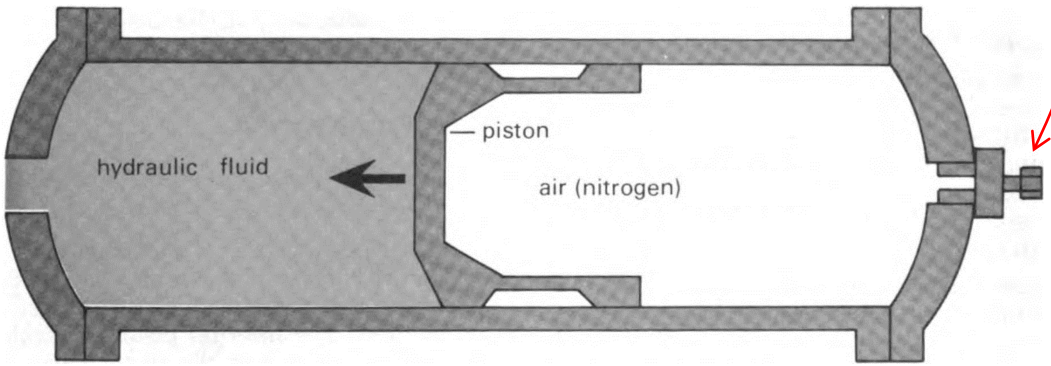


5: Hydraulic fluid flow rate & accumulator

- Usually, for flight control, the maximum flow rate is needed in a short duration and the resulting velocity is high.
  - To size up the pump might not be a wise approach.
- Thus, an accumulator is often used to enhance the flow rate
  - It contains a compressed gas cylinder
  - The gas augments the system pressure

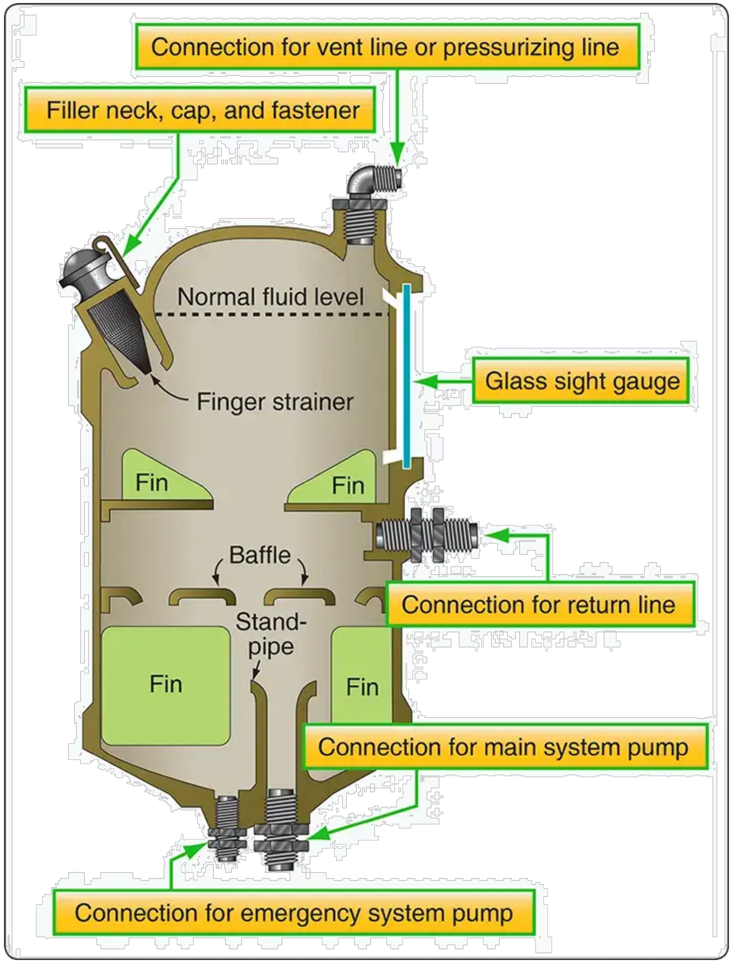
Frequency & maximum demands are known and adjusted by the accumulator



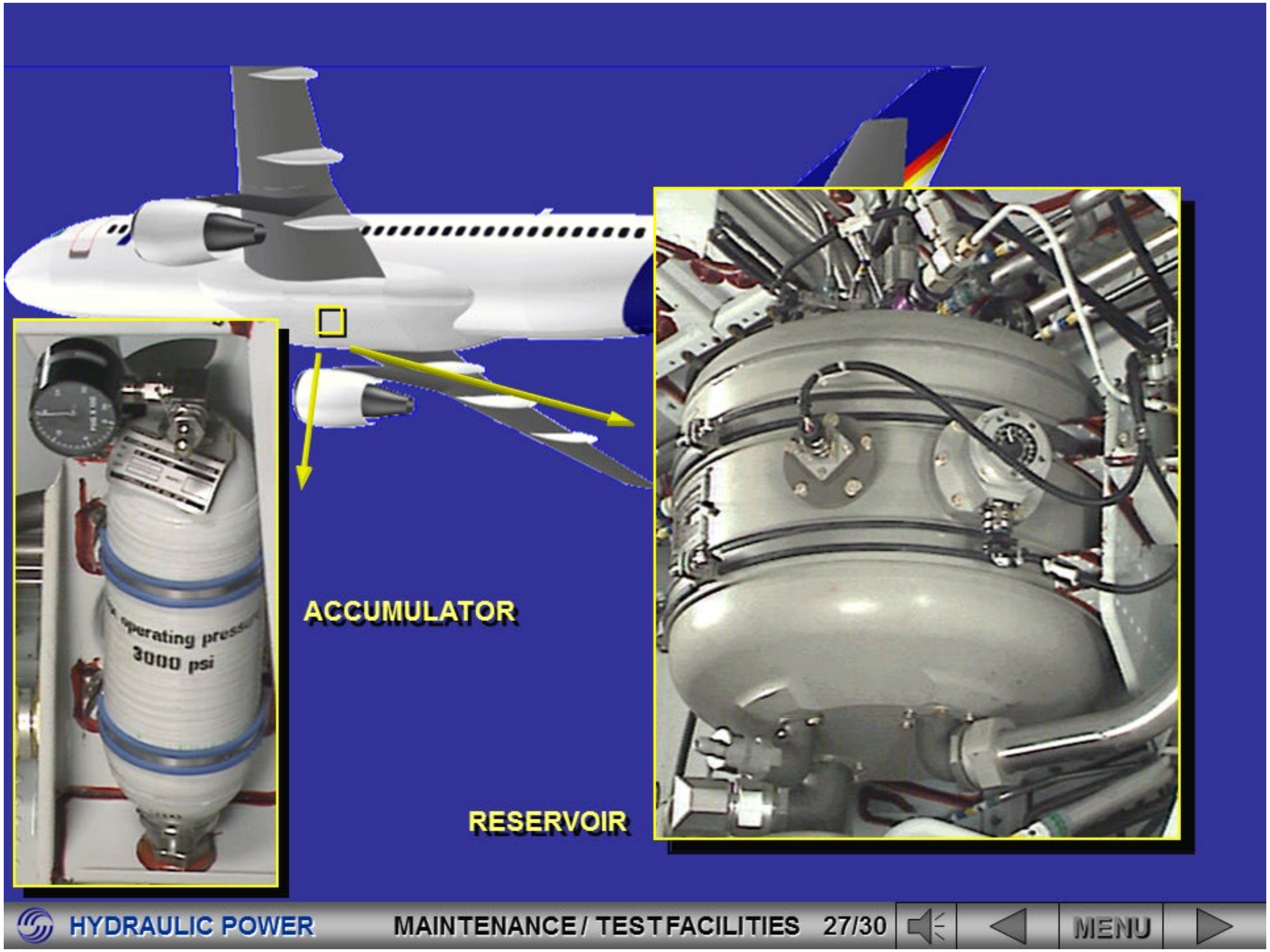


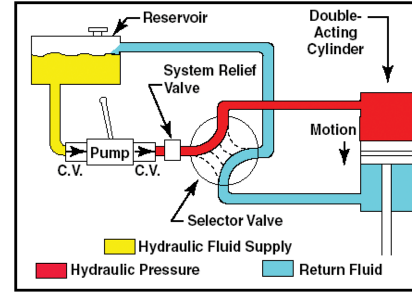
6: Hydraulic reservoir: overall

- A reservoir is a major part in the hydraulic system to supply the hydraulic fluid
- In addition to store the fluid in the tank, the reservoir should:
  - Assist the separation of contaminations: filters
  - Help dissipate heat generated in the whole system
  - Some reservoirs also contain magnetic plugs to trap iron or steel particles in the fluids



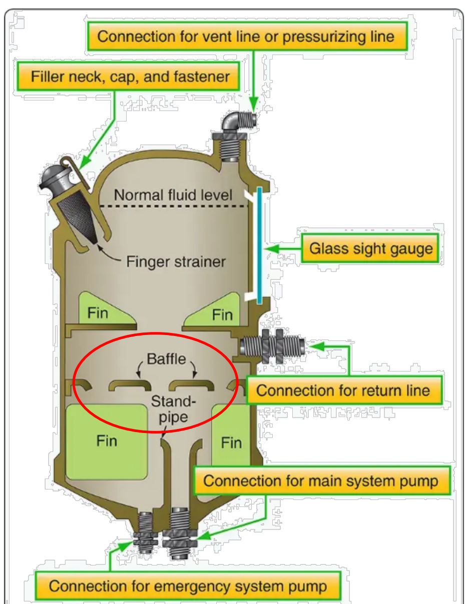
6: Hydraulic reservoir on aircraft

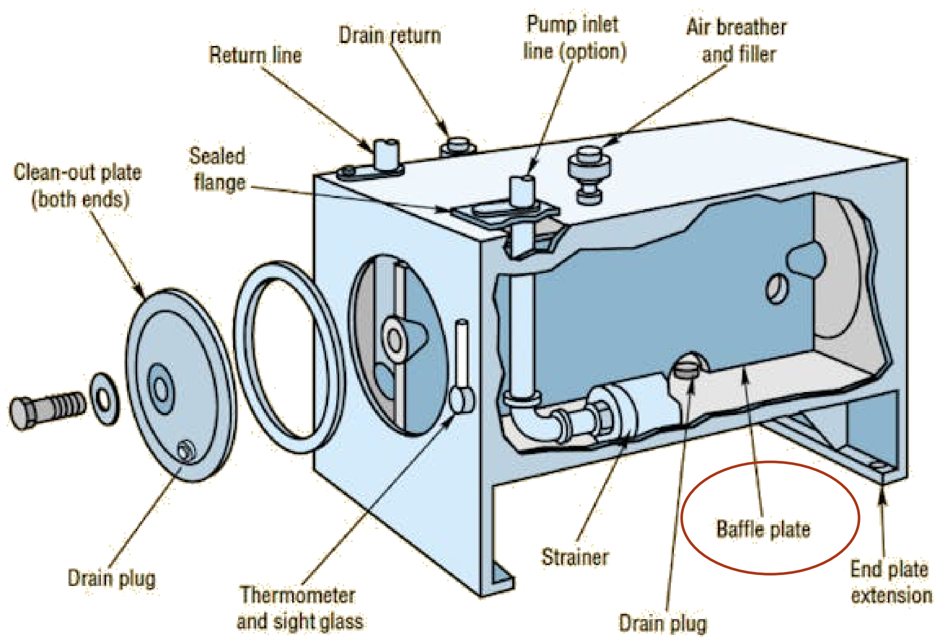




6: Hydraulic reservoir-Baffle plate

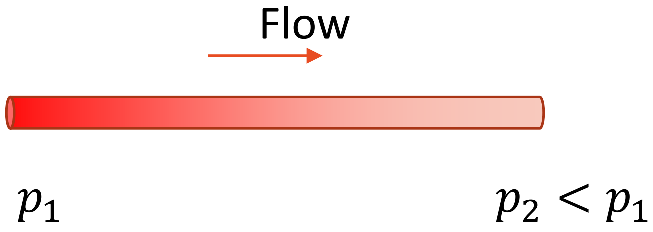
- Inside the reservoir, there is a baffle plate that is used to separate the pump inlet from the system to avoid the recirculation of the flow.
- As a result, the particles are allowed to settle to the bottom.
- It also helps keep a homogeneous temperature distribution in the system.

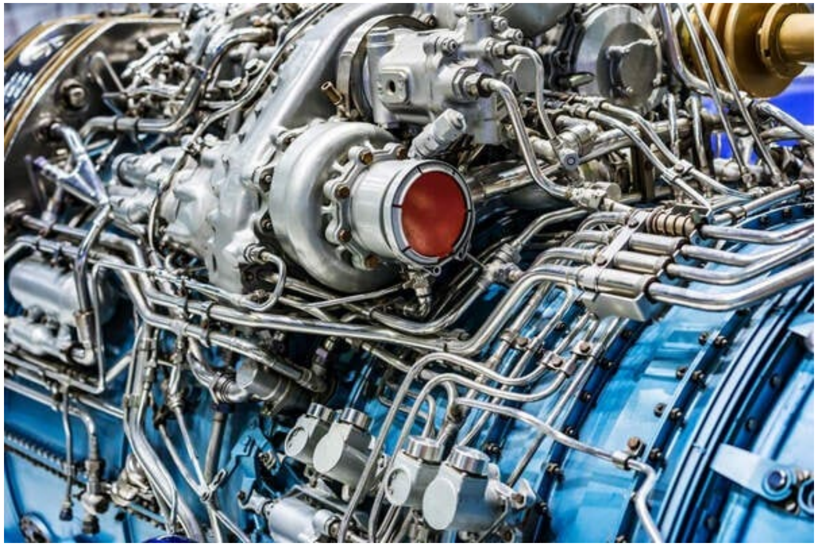




7: Hydraulic pipelines

- In aircraft, the hydraulic fluids are distributed on the aircraft through complex pipelines
- Flow along the pipes can experience pressure drops
- Length, diameter and layout of the pipes can be determined using expressions in pipe flows, but corrections are often needed



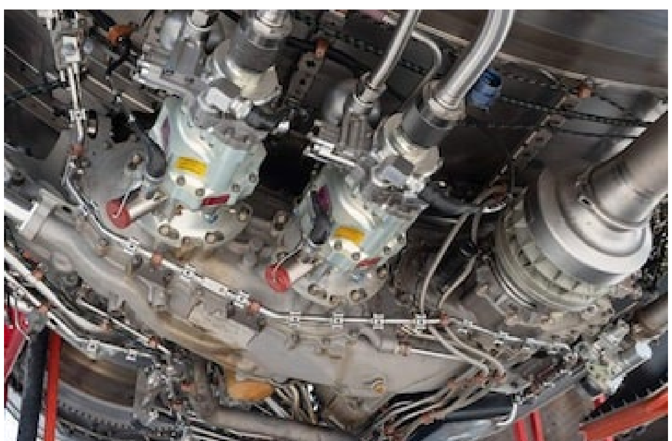


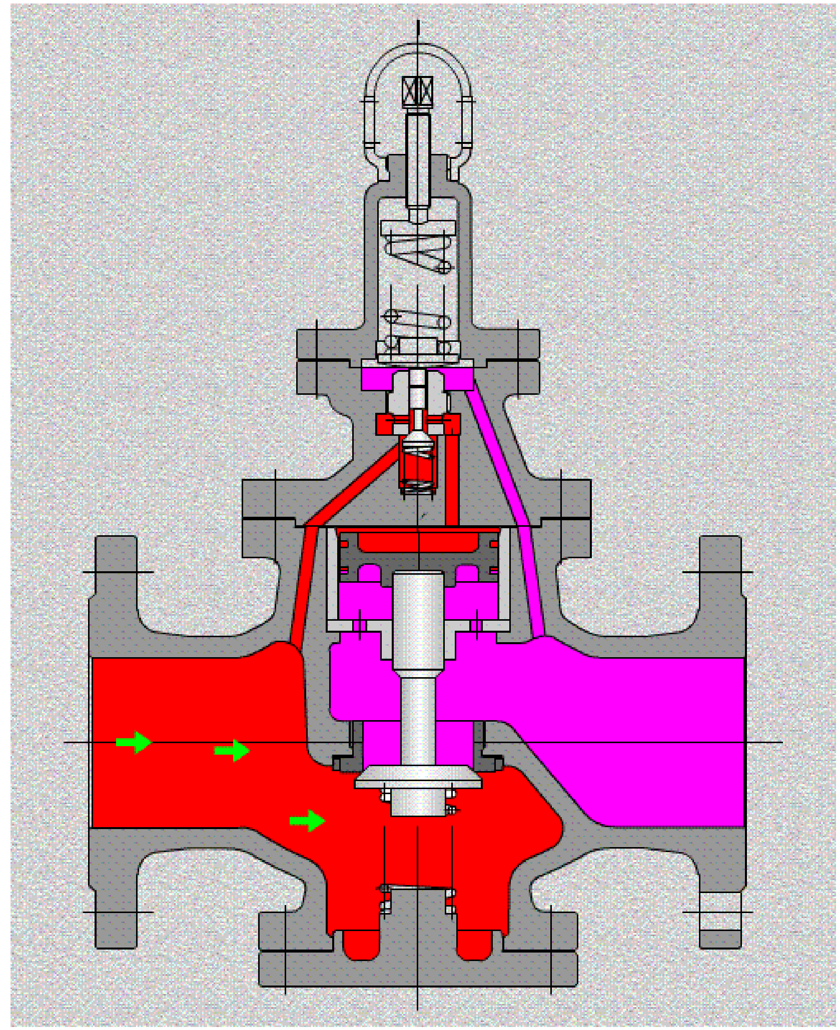
7: Hydraulic valves

- Valves are important in hydraulic pipeline systems to moderate the pressure, speed and flow directions.
- Common valves include:
  - Pressure relief valve/調壓閥: It is used to limit the maximum pressure in the circuit.
  - Flow control valve/流量控制閥: It is used to control the flow rate/flow speed in the hydraulic pipes
  - Direction control valve/方向控制閥: It is used to redirect the flow in the hydraulic systems pipes

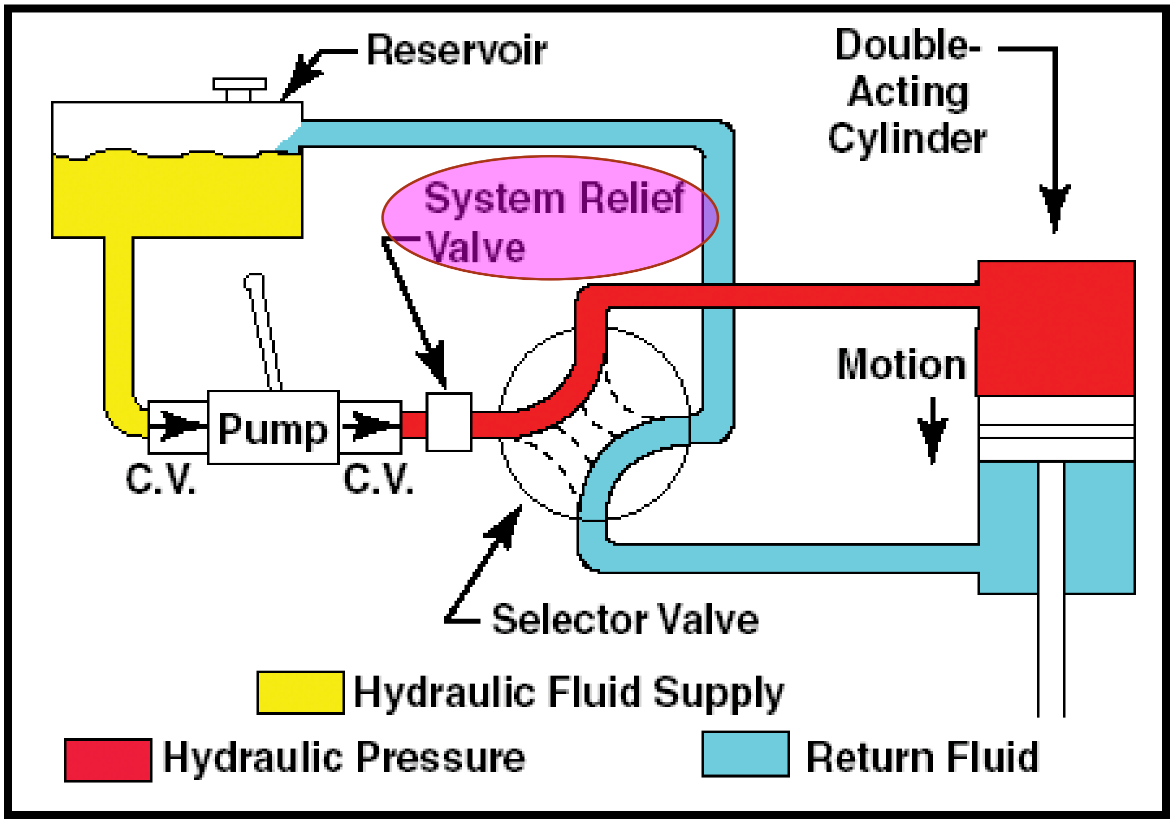
7: Hydraulic valves - pressure relief valve/调压阀

- In practice, every circuit with fixed-volume pump needs a pressure relief valve.
- It is normally a closed valve to limit the pressure to a specific maximum value by diverting pump flow back to the reservoirs





7: Hydraulic valves - pressure relief valve/调压阀



To control the flow rate

7. Hydraulic valves: flow control valve/流量控制阀

- Non-pressure-compensated valves:
  - They are used when the pressure is nearly constant and the speeds are not critical
  - The flow rate depends on the load at the outlet.

- Pressure-compensated valves:
  - They are used when there are pressure variations in the pipe
  - The pressure compensator acts to keep the pressure drop

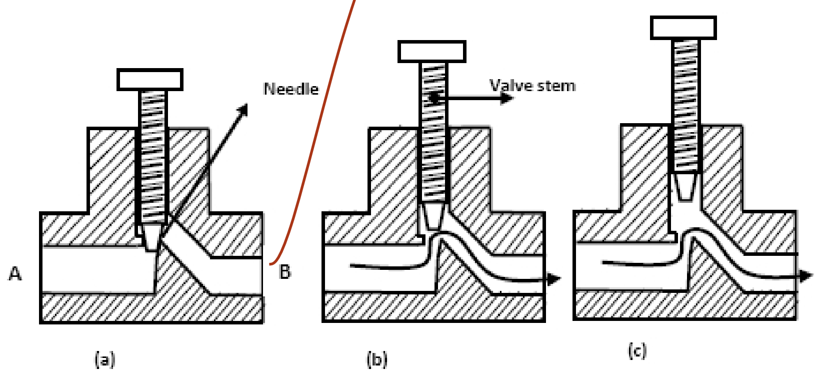
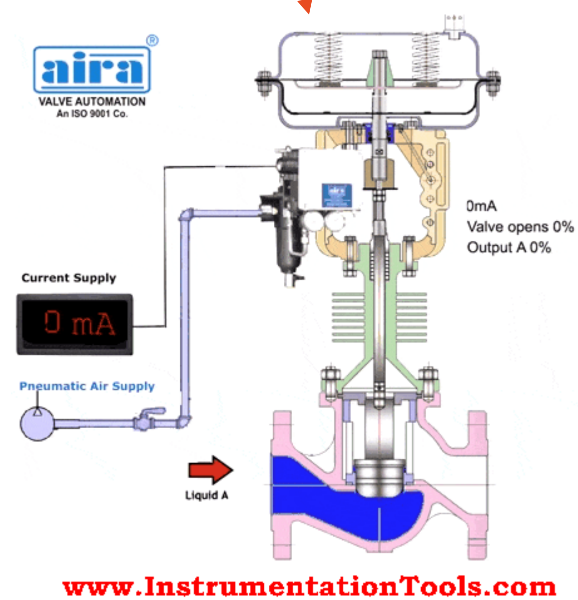
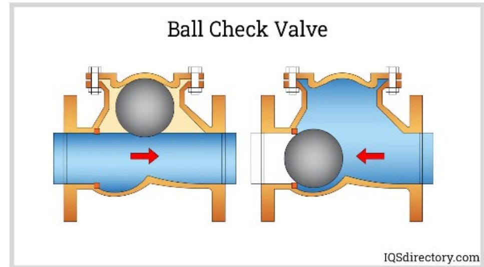


Figure 1.3 Non-pressure-compensated needle-type flow-control valve. (a) Fully closed; (b) partially opened; (c) fully opened.

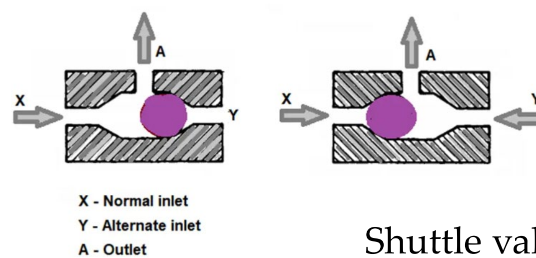


7. Hydraulic valves: direction control /方向控制阀

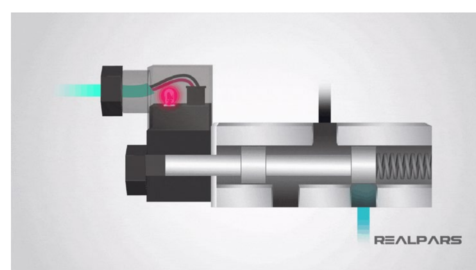
- The direction control valve (DCV) uses external signal, which could be mechanical, electrical, etc., to release, stop or redirect the flow.
- Types of the DCV:
  - Check valve (simplest)
  - Shuttle valve: allows two alternative flow sources to be connected to on branch
  - Spring spool valve (or selector valve, mostly used): use a sliding spool to change the flow path



Check valve



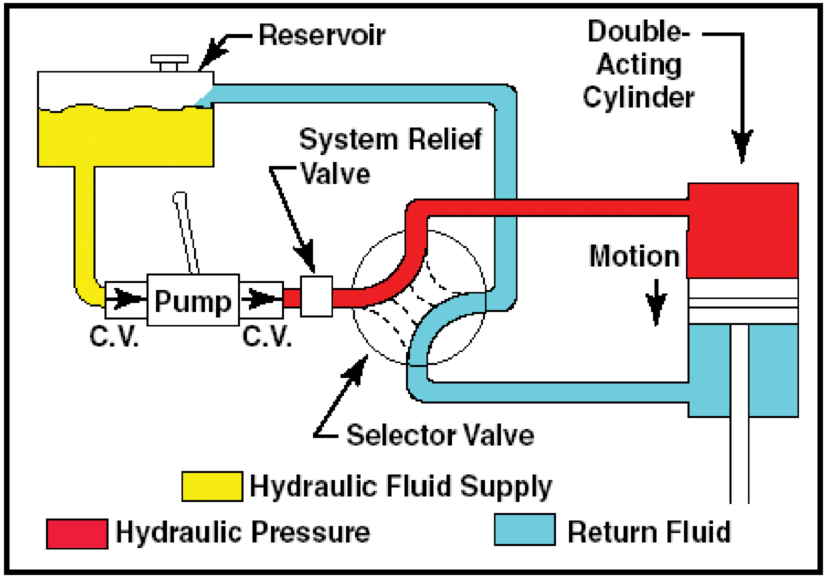
Shuttle valve



Selector valve

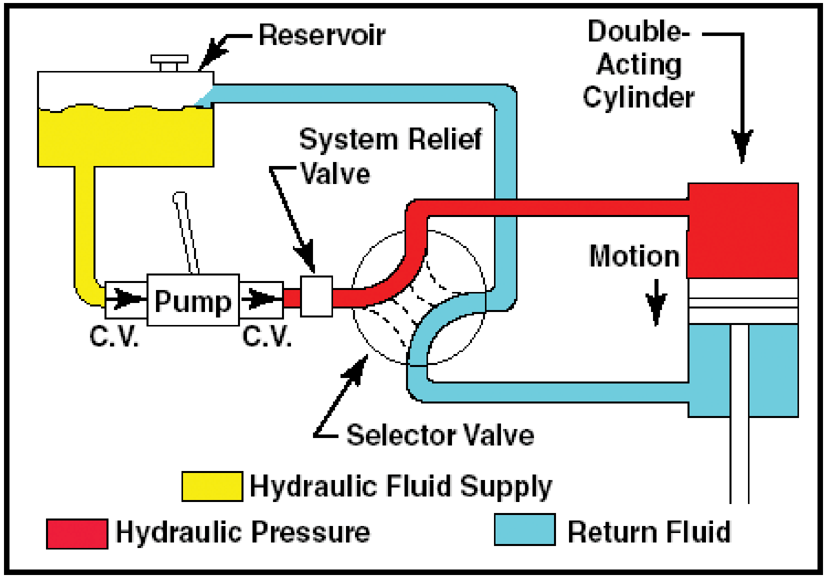
8. Hydraulic pumps

- To ensure the hydraulic system can work sustainably, the pipes will form circuits.
- The hydraulic pipes can be classified to the:
  - Pressure pipes/pressure lines
  - Return pipes/return lines



8. Hydraulic pumps

- To form a circuit, pumps are needed in the hydraulic pipeline
  - Pumps take the fluid from the container/reservoir to the pipe system.
- The fluid is pressurized after passing the pump
  - Flow motion generated by the pump does not generate pressure:
  - But the resistance to the flow by the valve (or discharge port) can increase the pressure.

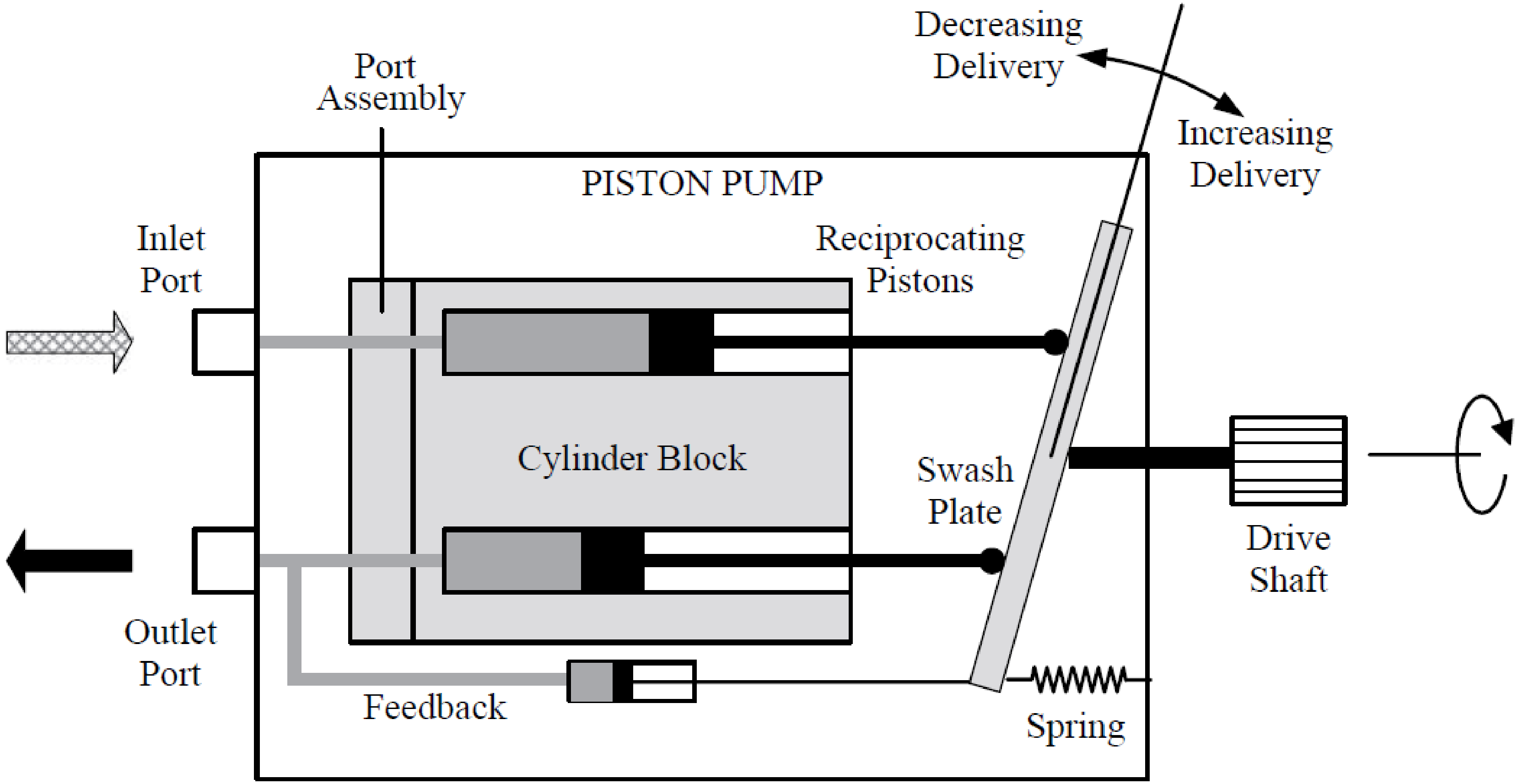


8. Hydraulic pumps

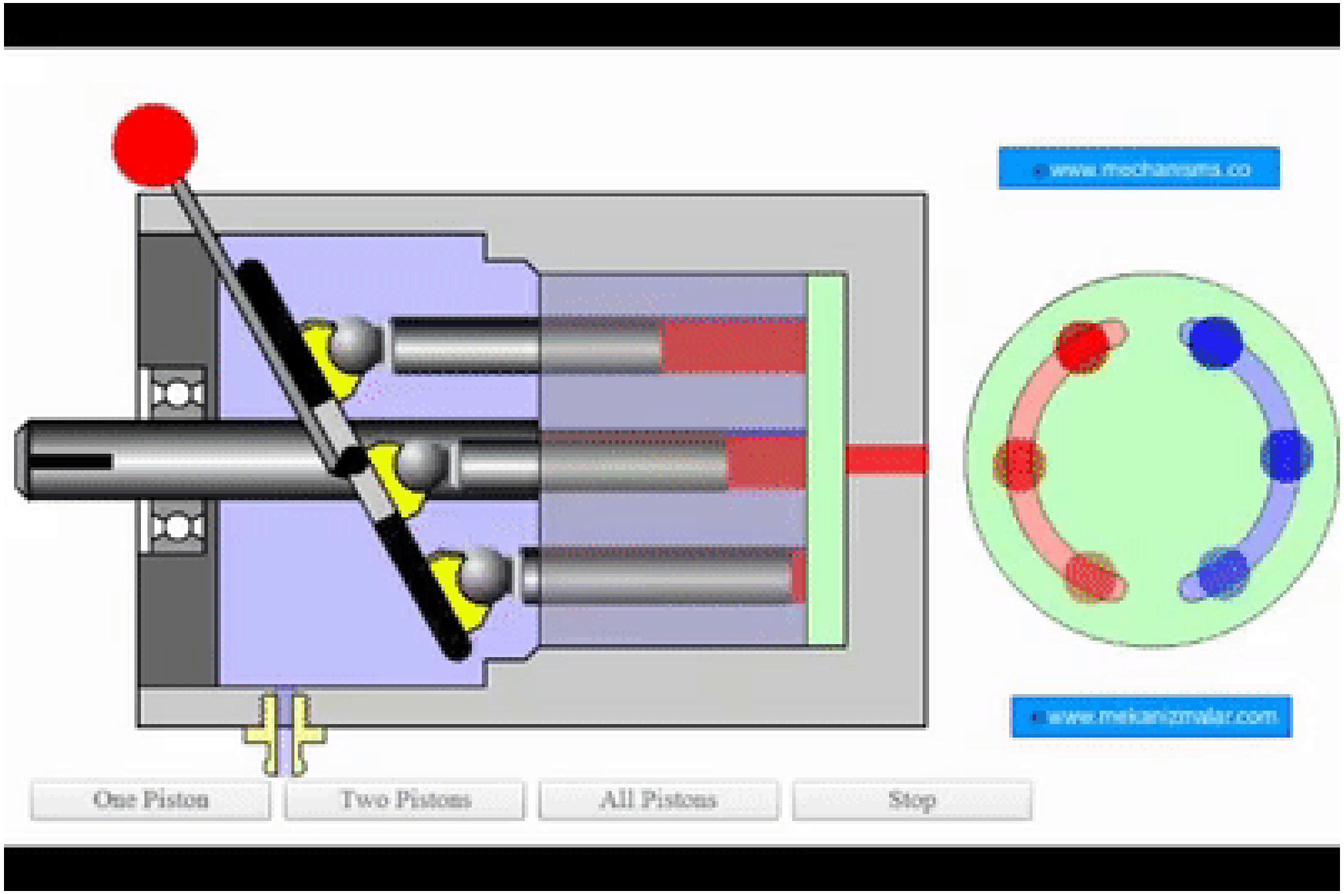
- Hydraulic pumps can be classified to:
  - Positive displacement pumps:
    - Fixed amount of fluid is taken from one end to the other
    - The flow amount is proportional to their displacement and rotation speed
    - The input and output regions are separated so that the flow cannot be leak back. It is often used in hydraulic systems
  - Non-positive displacement pumps (not often used in hydraulic systems)

- Examples of the positive displacement pumps
  - Gear pump (rotary)
  - Screw pump (rotary)
  - Vane pump (rotary)
  - Piston pump (reciprocating)

8. Example: piston pump



8. Example: piston pump

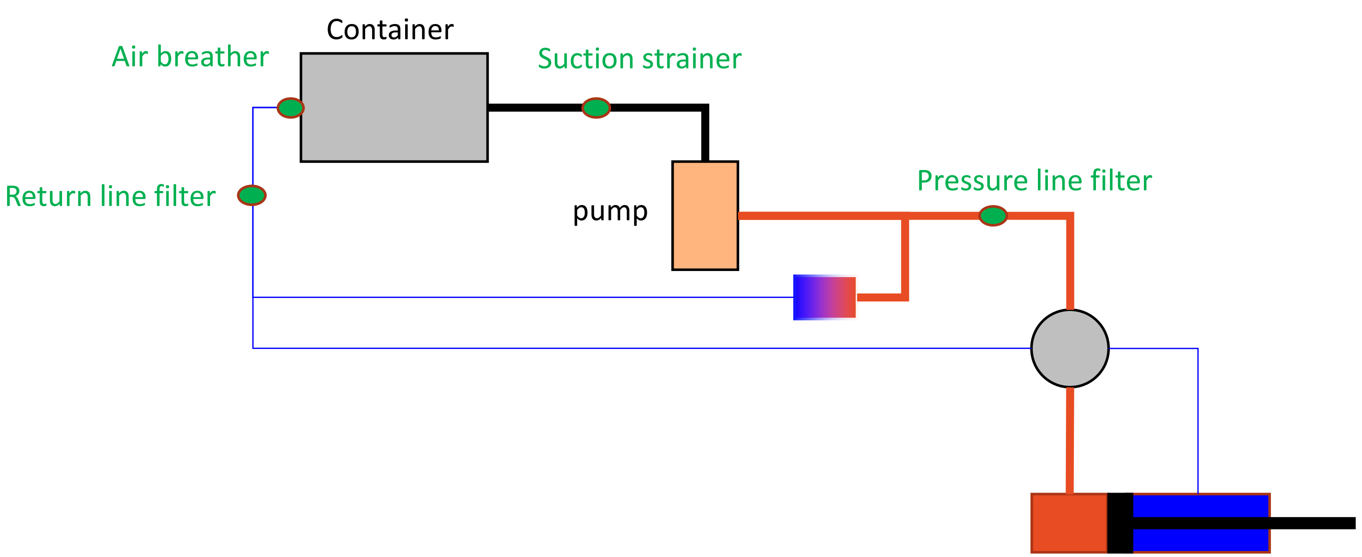


8. Hydraulic pumps

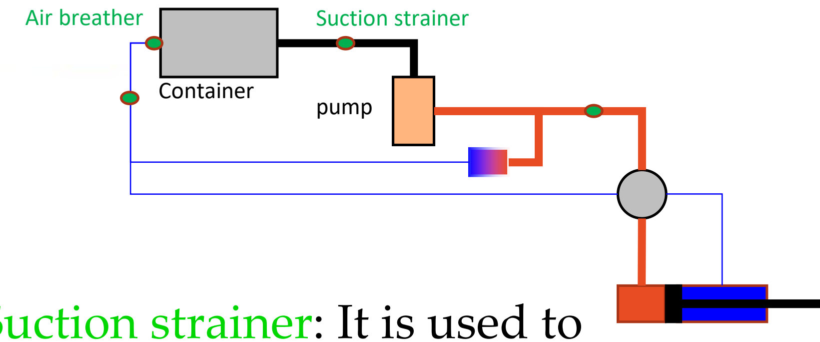
- Nevertheless, pumps are driven by external power to pressurize the fluid.
- The power is often provided by engine
- Sometimes, the power can also be provided by electric motors
- Usually, there will be multiple hydraulic systems in an aircraft. And their pumps will be connected to different engines.

9: Hydraulic filters

- Filters are used to remove the particles in the hydraulic system. They can be located at different parts of the hydraulic system:
  - Air breather: connected to the closed hydraulic tanks
  - Suction strainer: connected to the pump inlet
  - Pressure line filter: downstream of the hydraulic pump
  - Return line filter: between the control valve and reservoir



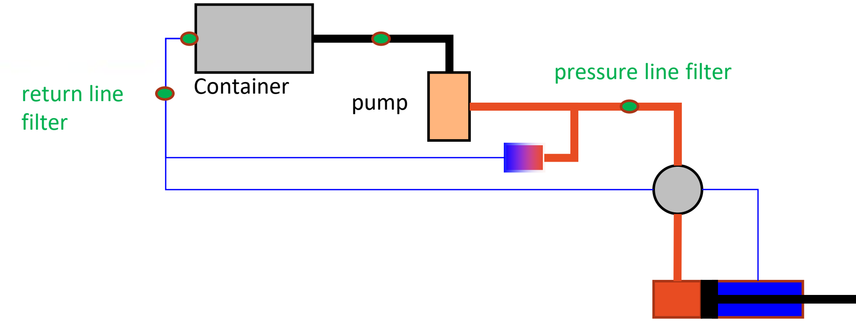
9: Hydraulic filters



- Air breather: It is connects the closed hydraulic reservoir with an air chamber to maintain the pressure on the hydraulic fluid
  - Air in: pressure raise
  - Air out: pressure drop
- Fine wires are also used to spilled out the dust and oil mist

- Suction strainer: It is used to remove large particles while the resistance to fluid is low.
  - It mainly consist of metal frame wrapped with fine-mesh screens
  - It is used at the pump inlet to ensure the pressure drop is minimal

9: Hydraulic filters



- Pressure line filter: it is located downstream the pump to protect the more sensitive components in the system.
  - It is used to remove the small size particles
- Return line filter: it is located at the control valve and the fluid reservoir to avoid the debris from the working comments are carried back to the reservoir
  - It is used to remove the common size particles

Pressure line filter example

Return line filter example

Power distribution

Power distribution

- In an aircraft, there are many components that need to be controlled by the hydraulic system.
- Different parts correspond to different working pressure, requiring various sources for pumping.
- Thus, it can be further classified, e.g.:
  - Green system
  - Yellow system
  - Blue system
- Each system has its own reservoir, and the hydraulic fluid of each system CANNOT be connected to the other one

The naming can be different for different aircraft!

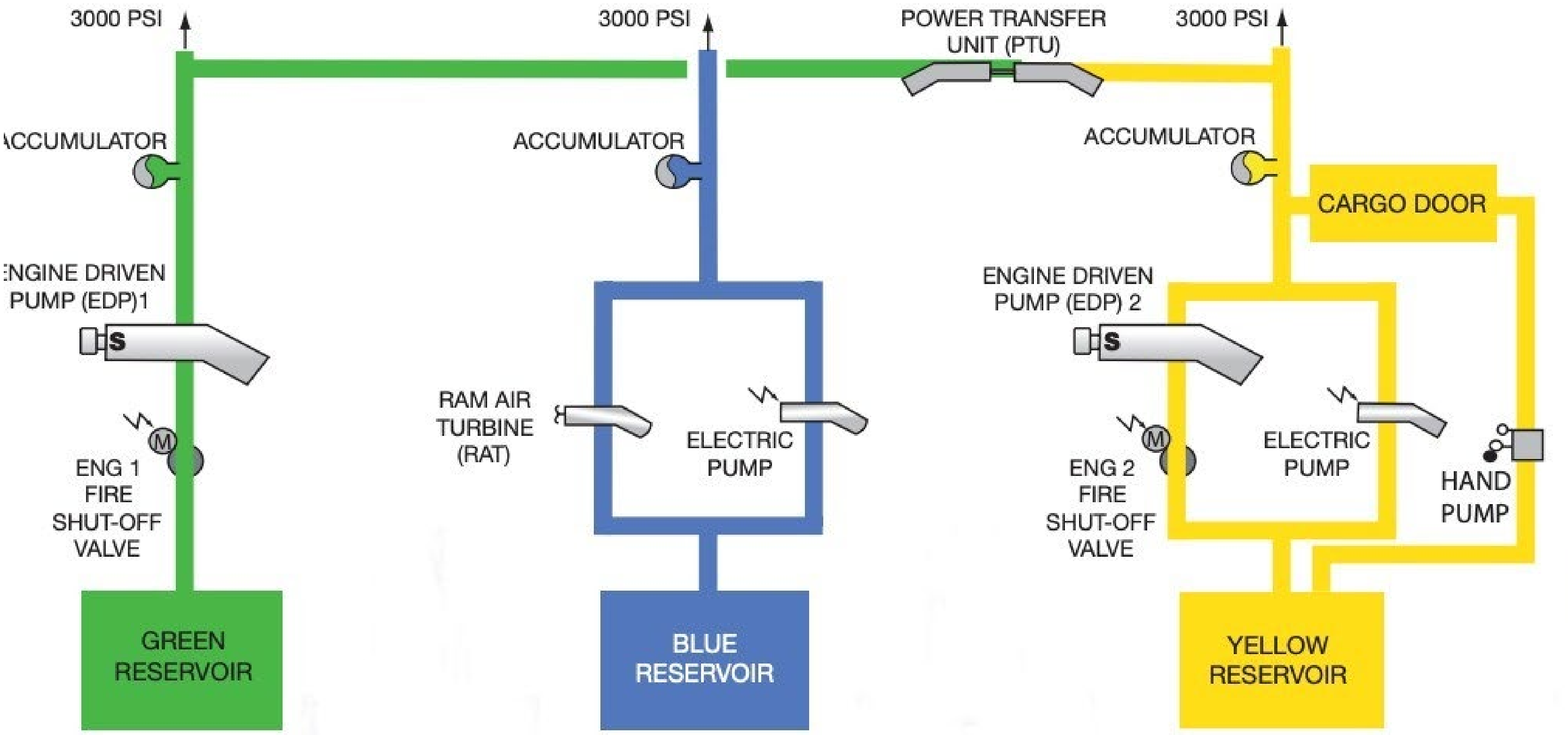
Power distribution

- For different aircraft, the hydraulic systems can be significantly different. The naming, pumping sources, and controlled parts are different, e.g.,
  - In Avro RJ aircraft, it contains a Yellow system and a Green system being pumped by two engines.
  - In Airbus A320, it contains a Yellow, a Green, and a Blue system being pumped by two engines and an electric driven motor
  - In a Boeing B767 aircraft, it contains a Left system (Red system), a Right system (Green system) and a Centre system (Blue system). The Red and Green systems are pumped by engines while the Blue system is pumped by two electric driven motors. A air-driven pump and a Ram Air Turbine are employed.

Example in Airbus A320

- Green system (system 1):
  - The fluid is pressurized by an Engine Driven Pump (EDP) located in No. 1 engine.
  - Typical flow rate: 140L/min
- Blue system (system 2):
  - The fluid is pressurized by an electric motor-driven pump. The typical flow rate is 23 L/min
  - In emergency conditions, a Ram Air Turbine (RAT) is used with flow rate about 78 L/min
- Yellow system (system 3):
  - The fluid is pressured by an EDP located in No. 2 engine
  - A electric motor driven pump for ground service operations
  - <u>A hand pump to pressurize the system for cargo door operation</u>

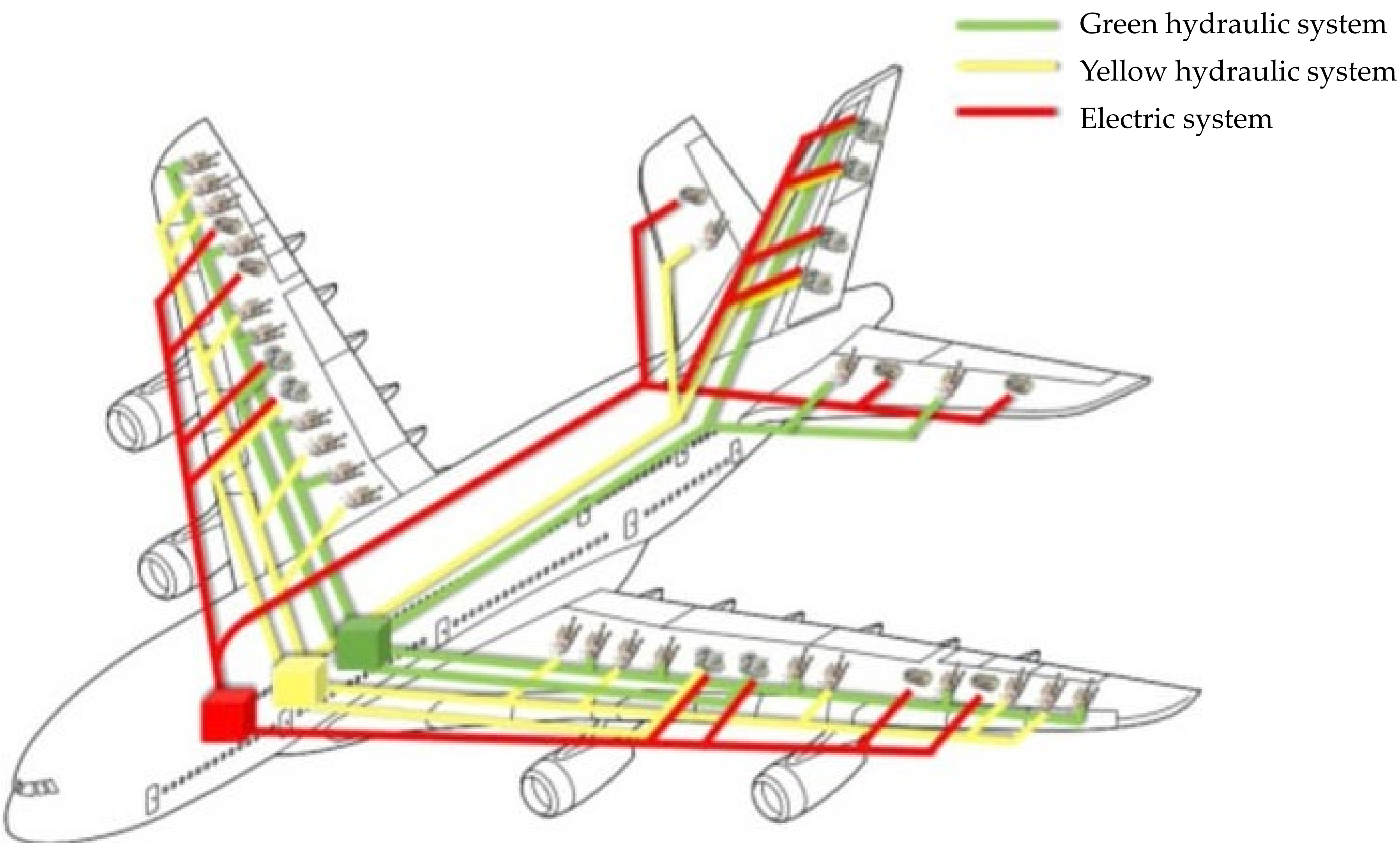
Example in Airbus A320



PTU (power transfer unit): a bidirectional power transfer units between Yellow and Green systems when the pressure difference is larger than 500 psi. This is a back-up in case there are failures of the engine or driven pump.

Hydraulic system distribution

Hydraulic system distribution



Summary

Summary

- A hydraulic system uses a fluid under pressure to drive the flight control surfaces, aircraft components and landing gear, etc.
- Basis for the hydraulic system: hydrostatics & Pascal's principle
- Principles and features of the majors components in a hydraulic system are introduced.
- A brief introduction to the power distribution of the aircraft hydraulic system.