Basics of signal processing, design of specimens, system acquisition

Description of actuation systems

Dr. Simone Peloso

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Principal testing methods

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The more common testing methods in the fields of civil and earthquake engineering are

- Quasi-static loading testing method;
- Shaking table testing method;
- Effective force method;
- Pseudo-dynamic testing method;
- Real time pseudo-dynamic testing method;
- Real time dynamic hybrid testing method;
- Centrifuge tests.

Despite the selected testing method, forces or displacements are always applied to the specimen to investigate its behaviour.

The application of such excitations are performed using an actuation system.

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Actuation system

The actuation system is used to apply an excitation to the structure under investigation.

Generally speaking, it is possible to distinguish two main groups:

- hydraulic actuation system

- electric actuation system

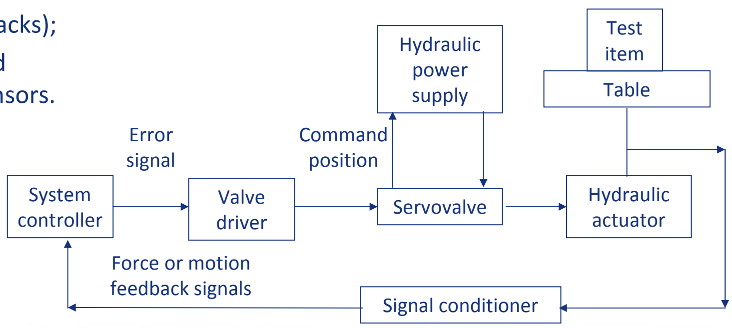
The choice between one or the other system depends by the research needs and the available resources.

Both of them have advantages and disadvantages that make them suitable for different applications.

Hydraulic actuation system

In general, a hydraulic actuation system includes the following components:

- hydraulic power system;
- accumulators;
- piping system;
- manifolds;
- servo valves;
- actuators (or jacks);
- controllers and associated sensors.



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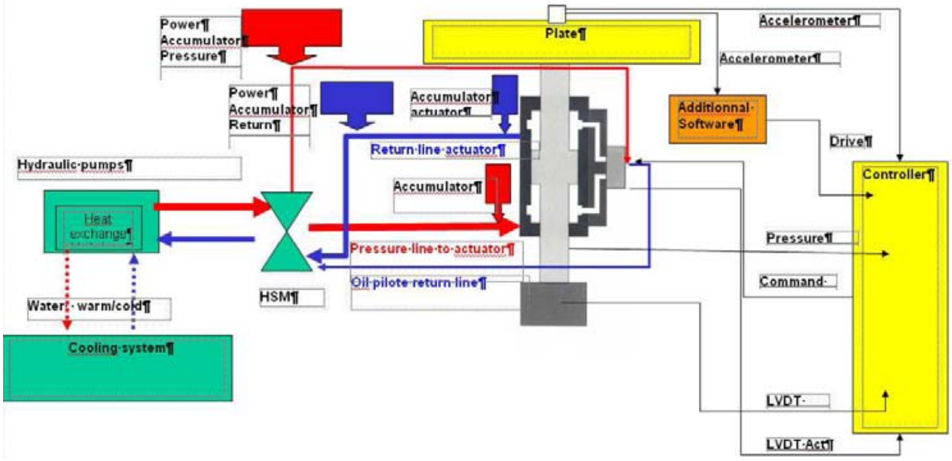

Hydraulic actuation system

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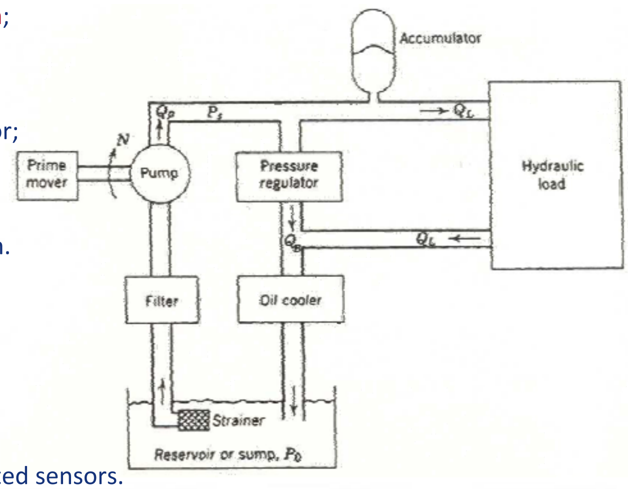
In general, a hydraulic actuation system includes the following components:

- hydraulic power system;
  - engine;
  - pump;
  - pressure regulator;
  - tank;
  - filtration system;
  - oil cooling system.
- accumulators;
- piping system;
- manifolds;
- servo valves;
- actuators (or jacks);
- controllers and associated sensors.



Hydraulic power system

The hydraulic power system is the ensemble of components giving the power to the actuation system.

Although all the components must be adequate to their role to assure the proper behaviour of the entire testing system, the heart of the power system is represented by the pump.

This element, actually one or more connected in series or parallel, must be chosen considering a number of parameters: the flow rate of oil necessary to operate the testing system, the oil pressure required to apply the desired forces.

For our applications, a pump can be considered as a machine transporting and giving pressure to fluids which in turn are used to operate other devices

Pumps

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In general, pumps can be divided in two big families:
- (i) hydrodynamic pumps: big flow, low pressure;
- (ii) volumetric pumps: relatively small flow, high pressure.

Volumetric pumps move the fluids using the variation of volume of their inner chambers. In this way, a volumetric pump convert the mechanical power of the engine into hydraulic power, this last is proportional to the product between the flow (Q) and the pressure (p) of the fluid.

Different types of pumps are available on the market and can be used within the hydraulic power system:
- Gear pumps
- Vane pumps
- Radial-piston pumps
- Axial-piston swash-plate pump

Gear pumps

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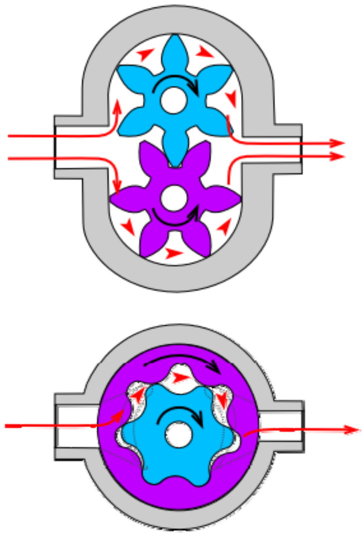
A gear pump pumps the fluid by displacement.

They are one of the most common types of pumps for hydraulic fluid power applications and they can operate also with viscose fluids.

There are two main variations:

- external gear pumps which use two external spur gears;
- internal gear pumps which use an external and an internal spur gear.

Gear pumps are positive displacement (or fixed displacement), meaning they pump a constant amount of fluid for each revolution.



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Vane pumps

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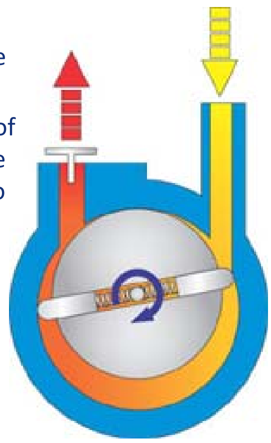
A rotary vane pump is a positive-displacement pump that consists of vanes mounted to a rotor that rotates inside of a cavity. In some cases these vanes can be variable length and/or tensioned to maintain contact with the walls as the pump rotates.

The simplest vane pump is a circular rotor rotating inside of a larger circular cavity. The centres of these two circles are offset, causing eccentricity. Vanes are allowed to slide into and out of the rotor and seal on all edges, creating vane chambers that do the pumping work.

On the intake side of the pump, the vane chambers are increasing in volume. These increasing volume vane chambers are filled with fluid forced in by the inlet pressure. Inlet pressure is actually the pressure from the system being pumped.

On the discharge side of the pump, the vane chambers are decreasing in volume, forcing fluid out of the pump.



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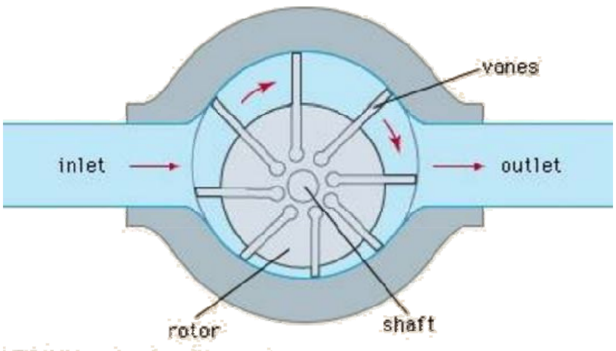
Vane pumps

Additionally, the vane pump can easily become a variable displacement pump.

The centreline distance from the rotor to the eccentric ring is used to determine the pump's displacement. By allowing the eccentric ring to pivot or translate relative to the rotor, the displacement can be varied.

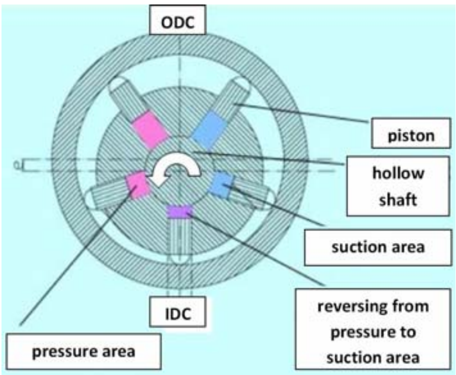


Radial-piston pumps

A radial piston pump is a form of hydraulic pump. The working pistons extend in a radial direction symmetrically around the drive shaft.

The outer ring for bracing of the pumping pistons is in eccentric position to the central hollow shaft. This eccentricity determines the stroke of the pumping piston.

The piston starts in the inner dead centre (IDC) with suction process. After a rotation angle of 180° it is finished and the workspace of the piston is filled with the to moved medium. The piston is now in the outer dead centre (ODC). From this point on the piston displaces the previously sucked medium in the pressure channel of the pump



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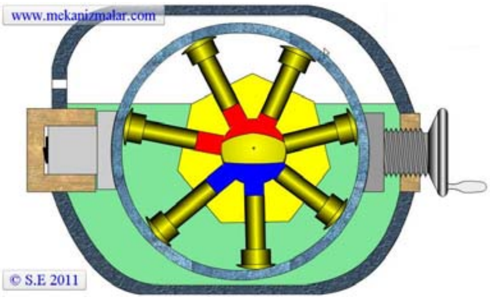
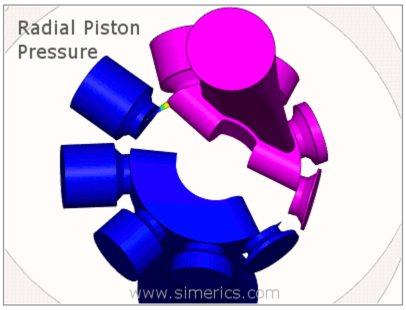
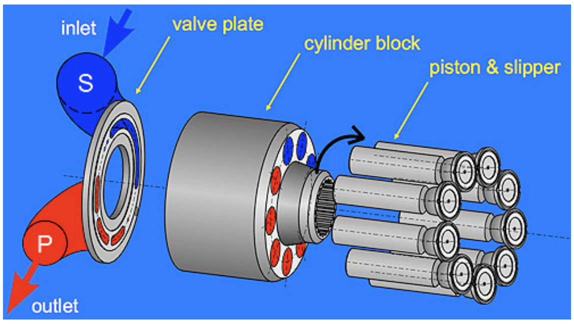




Axial-piston swash-plate pumps

An axial piston pump is a positive displacement pump that has a number of pistons in a circular array within a cylinder block.

An axial piston pump has a number of pistons arranged in a circular array within a housing which is commonly referred to as a cylinder block, rotor or barrel. This cylinder block is driven to rotate about its axis of symmetry by an integral shaft that is, more or less, aligned with the pumping pistons (usually parallel but not necessarily).



Axial-piston swash-plate pumps

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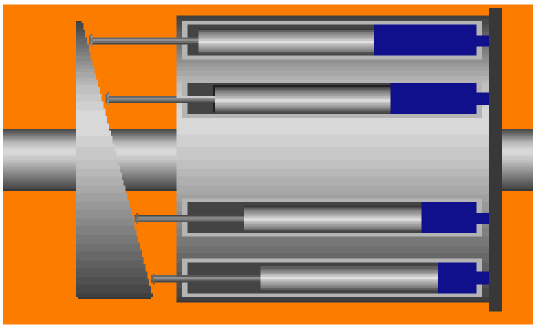

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Piping system

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The piping system connects the various parts of the hydraulic actuation system.

The piping system is composed by:
- pipes (rigid w/o welding or flexible);
- fittings;
- flanges.

For the connection of the elements of the piping system flanged or threaded connectors are normally used.

The design of the components of the piping system must be performed depending on the working and peak pressures and flows.

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Cooling system

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A proper cooling system must be designed both for the pumping system and the oil. The heat load is the energy that is put into the hydraulic oil under full flow conditions and which must be subsequently removed by the heat exchangers.

The hydraulic pumps are generally air or water cooled with specific cooling equipment systems including cooling towers, thermal mass (big tank) systems with circulation pumps, and local city water supplies.

As a result of experience, conventional cooling towers system is a good solution but introduce same restraint about legionella control (pulmonary disease) .

Concerning the oil, as always, transferring power from an engine to a machinery, part of the input power is transformed in thermal power. In the case of hydraulic actuation system, the most of this is transferred to the oil increasing its temperature and possibly causing problems.

Cooling system

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Generally speaking, overheating can produce problems such as:

- overheating of the oil (lower viscosity, lower lubricant power, needs for frequently replace the oil);

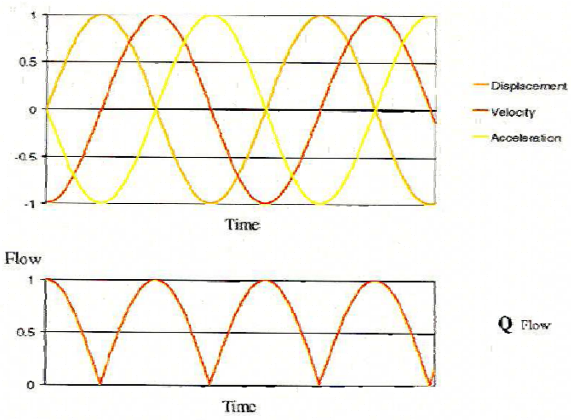
- overheating of hardware components (increase of mechanical clearances, damages to seals, change in control precision).

There are several important factors to consider when selecting cooling equipment. The most significant of these is the climate, particularly critical in case of often high ambient temperatures and high humidity.

Accumulators

The actuators are alimented by means of pumps which give oil with a given pressure and temperature. To increase the performances and to take into account the fast variation of pressure and flow during dynamic motion, some accumulators are placed on the actuators near the input and output.

The pumps give a continuous flow. When the flow through the actuator decrease, the pressure increases and the oil fills up the accumulator (input). When the flow is over the continuous flow, the pressure decrease and the accumulator discharges the oil through the actuator.



Accumulators

The aims of accumulators are:

- to increase the performances of the actuator (distortion and velocity)
  [accumulator pressurized at 125 bars]

- to decrease hydraulic shocks in the piping (return line)
  [accumulators pressurized at 3 bars]

Accumulators can be placed directly on the hydraulic line to increase the power or the global flow of the testing facility. The accumulators are pressurized when the pumps starts and they give flow for a short duration when the testing facility needs oil.

Accumulators

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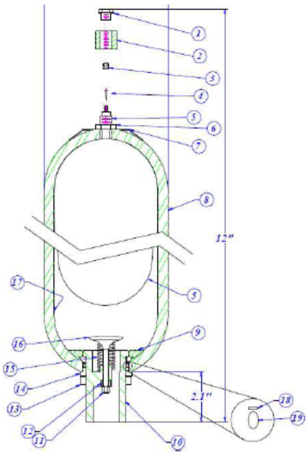
It is possible to distinguish between bladder and piston accumulators.

Bladder accumulators

They consist of a pressure vessel and an internal elastomeric bladder that contains the gas. The bladder is charged through a gas valve at the top of the accumulator, while a poppet valve at the bottom prevents the bladder from being ejected with the out-flowing fluid.
The poppet valve is sized so that maximum volumetric flow (typically from 15 l/s and up to 140 l/s for high-flow designs) cannot be exceeded.
The bladder can be replaced, usually through the fluid end of the vessel.



List of Component Parts	
	Description
1	Safety Cap
1	Safety Cap O-Ring
2	Protective Cap
3	Valve Cap
4	Valve Core
5	Bladder Kit[5]
	Buna-Nitrile
	Butyl
	EPR
	Fluorocarbon
	Hydrin
	Low Temp Buna
6	Hex Jam Nut
7	Name Plate
8	Caution Label
8	Information Label
9	Anti-Extrusion Ring
	Buna-Nitrile
	EPDM
	Fluorocarbon
10	Fluid Port[4]
11	Stop Nut
12	Piston
13	Locknut
14	Spacer
15	Spring
16	Poppet
17	Shell (3000 psi)
18	Metal Back-Up Ring
19	O-Ring
	Buna-Nitrile
	Butyl
	EPR
	Fluorocarbon

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Accumulators

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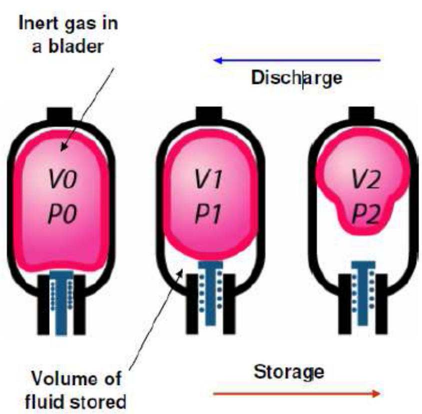
It is possible to distinguish between bladder and piston accumulators.

Bladder accumulators

To operate, the bladder is charged with gas (nitrogen) to a pressure specified by the manufacturer according to the operating conditions. When system pressure exceeds gas-precharge pressure of the accumulator, the poppet valve opens and hydraulic fluid enters the accumulator. The change in gas volume in the bladder between minimum and maximum operating pressure determines the useful fluid capacity.



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Accumulators

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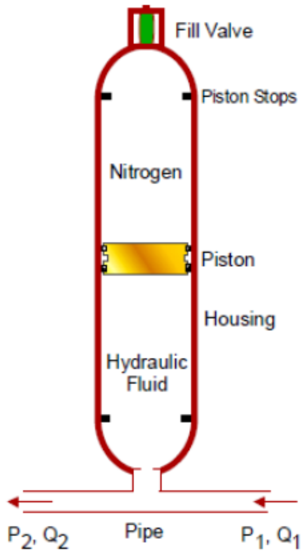
Piston accumulators

They have an outer cylinder tube, end caps, a piston element, and sealing system.

The cylinder holds fluid pressure and guides the piston, which forms the separating element between gas and fluid. Charging the gas side forces the piston against the end cover at the fluid end. As system pressure exceeds the minimum operating level for the accumulator, the piston moves and compresses gas in the cylinder.



Each type of separated, hydro-pneumatic accumulator has advantages, but bladder designs are generally considered the most versatile. For shock and pulsation, for example, bladder models are ideal. Piston units are not recommended because they are too slow to react to shock waves

Manifolds

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In engineering, a manifold is a structure or machine element that splits a flow of fluid from one channel into multiple channels or, vice versa, collects flow from multiple channels into one.

A hydraulic manifold is a manifold that regulates fluid flow between pumps and actuators and other components in a hydraulic system. It is like a switchboard in an electrical circuit because it lets the operator control how much fluid flows between which components of a hydraulic machinery.

A manifold is composed of assorted hydraulic valves connected to each other. It is the various combinations of states of these valves that allow complex control behaviour in a manifold. Additionally, manifolds decouple hydraulic circuits and perform interlocks and emergency pressure release.

Servo valves

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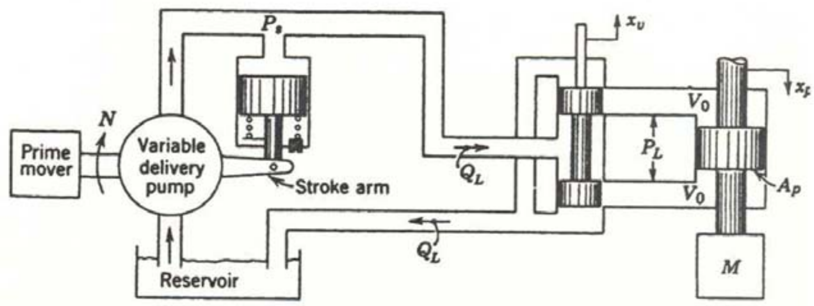
The servo valve is a kind of hydraulic amplifier which gives oil to the actuator as function of a low level signal.

An electro-hydraulic servo valve (EHSV) is an electrically operated valve that controls how hydraulic fluid is ported to an actuator. Servo valves and servo-proportional valves are operated by transforming a changing analogue or digital input signal into a smooth set of movements in a hydraulic cylinder. Servo valves can provide precise control of position, velocity, pressure and force with good post movement damping characteristics.



Servo valves

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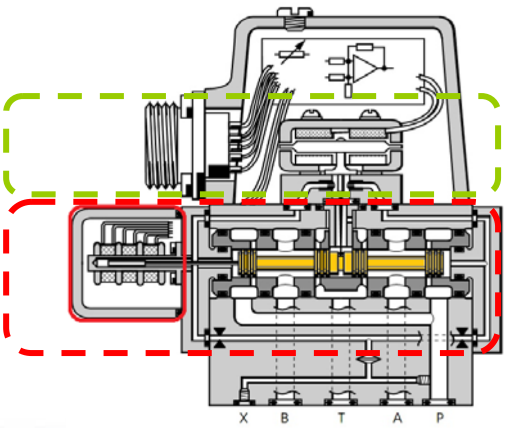
Principle of operation

An electric command signal is applied to the integrated position controller which drives the pilot stage. The thereby deflected **nozzle flapper system** produces a pressure difference across the drive areas of the **spool** and effects its movement.

Pilot or first stage

Power or second stage



Servo valves

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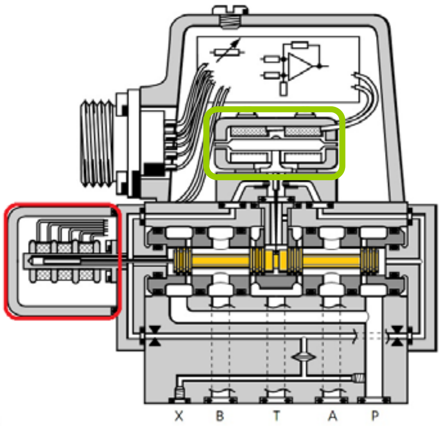
Principle of operation

An electric command signal is applied to the integrated position controller which drives the pilot stage. The thereby deflected **nozzle flapper system** produces a pressure difference across the drive areas of the **spool** and effects its movement.

The **position transducer** (LVDT) which is excited via an oscillator measures the position of the spool (actual value, position voltage). This signal is then demodulated and fed back to the controller where it is compared with the command signal. The controller drives the pilot stage until the error between command signal and feedback signal will be zero. Thus the position of the spool is proportional to the electric command signal.



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Servo valves

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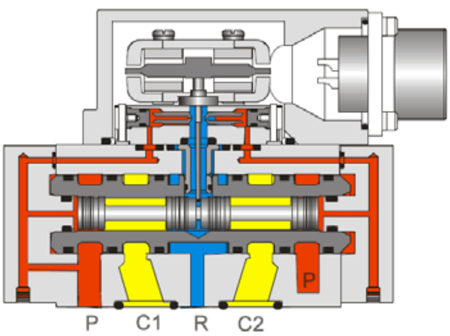
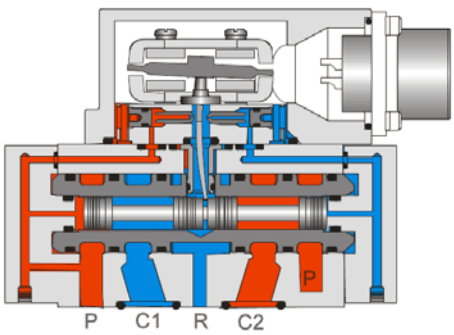
Principle of operation

Fluid continuously flows from the supply pressure “P” through both inlet orifices, through the nozzle flapper chamber then to return “R”.

The rocking motion of the armature/flapper throttle flows through one nozzle or the other.





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Servo valves

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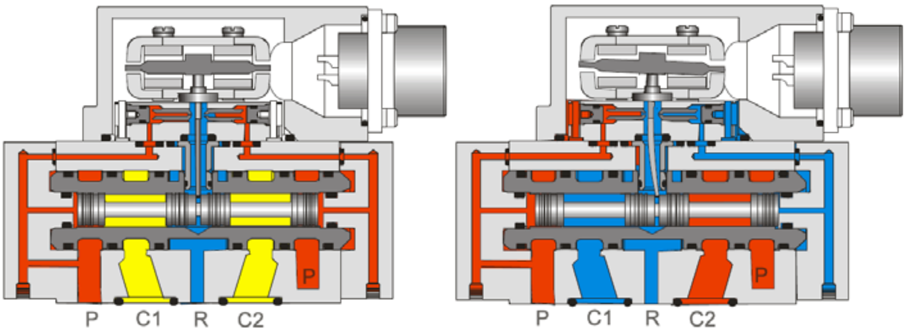
Pilot or first stage (hydraulic amplifier)

Armature and Flapper are rigidly joined and supported by a thin wall flexure tube.

Fluid continuously flows from the supply pressure “P” through both inlet orifices, through the nozzle flapper chamber then to return “R”.

The rocking motion of the armature/flapper displaces the spool inside the bushing (in the power stage).



Servo valves

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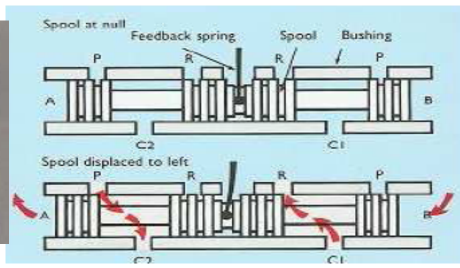
Power or second stage (valve spool)

The 4 way Spool slides within the Bushing or Sleeve. The bushing contains holes that connect to supply pressure “P” and return “R”.

At “Null”, the spool is centred in the bushing; spool lands cover “P” and “R” openings. Spool motion to either side of null allows fluid to flow from “P” to one of the control port and from the other control port “R”.

[Bushing or Sleeve]

[Spool]



Servo valves

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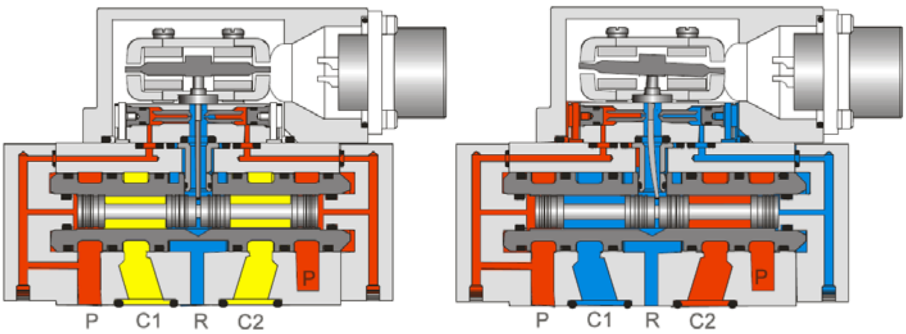
Power or second stage (valve spool)

The 4 way Spool slides within the Bushing or Sleeve. The bushing contains holes that connect to supply pressure “P” and return “R”.

At “Null”, the spool is centred in the bushing; spool lands cover “P” and “R” openings. Spool motion to either side of null allows fluid to flow from “P” to one of the control port and from other control port “R”.



Servo valves

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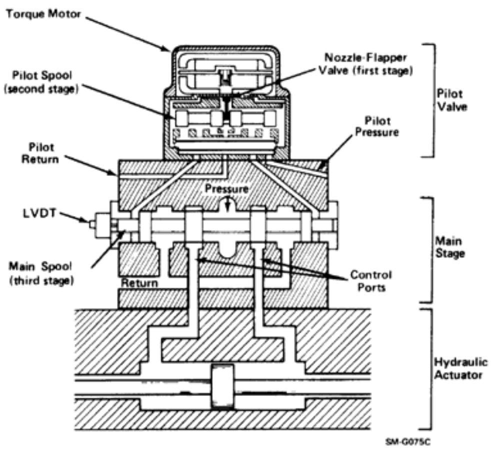
Three Stages Servo Valve

Commonly, the servo valve is then connected to a “Main stage” (or third stage).

The main spool here included operates as the pilot spool diverting the oil flow to one or the other control ports and hence to the chambers of the actuator.

Differently from the pilot spool, the main spool is not displaced by the nozzle, but it is controlled by the pilot pressure coming from the second stage.

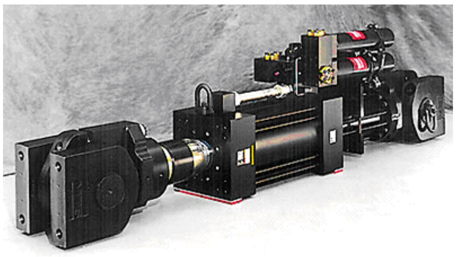


Hydraulic actuators

Generally speaking, an actuator is a type of motor for moving or controlling a mechanism or system. It is operated by a source of energy (e.g. hydraulic fluid pressure), and converts that energy into some kind of motion.

An actuator is the mechanism by which a control system acts upon an environment.

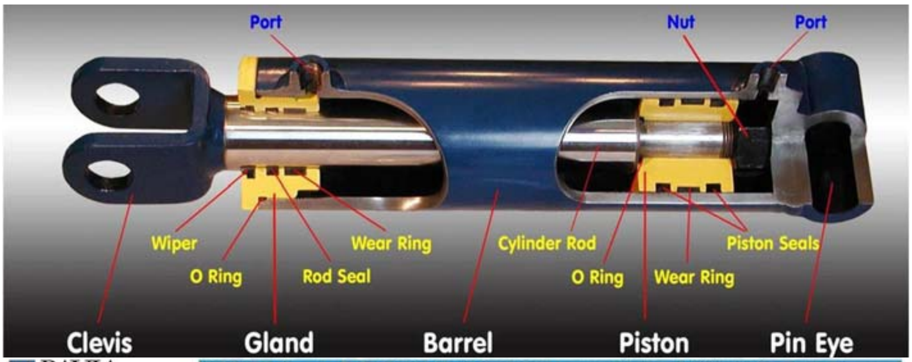
Within our scope, hydraulic actuators often are hydraulic cylinders (also called a linear hydraulic motors): mechanical actuators used to give a unidirectional force through a unidirectional stroke.



Hydraulic actuators

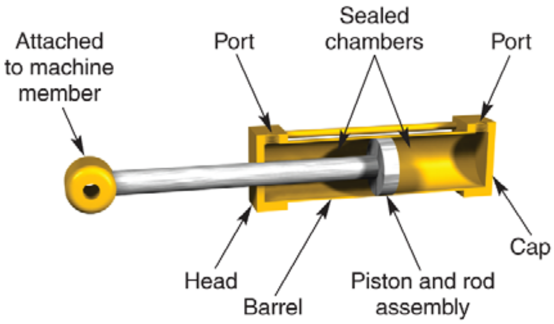
An actuator is composed by:

- a cylinder with hydrostatic bearings or special bearings with very low friction coefficient;
- a piston;
- a piston rod;
- two swivels (one at each extremity);
- one or several servo valves;
- a small LVDT in the servo valve;
- a LVDT transducer in the piston;
- a pressure sensor;
- some time a load cell.



Hydraulic actuators

The hydraulic cylinder consists of a cylinder barrel, in which a piston connected to a piston rod moves back and forth. The barrel is closed on one end by the cylinder bottom (also called the cap) and the other end by the cylinder head (also called the gland) where the piston rod comes out of the cylinder. The piston has sliding rings and seals. The piston divides the inside of the cylinder into two chambers, the bottom chamber (cap end) and the piston rod side chamber (rod end / head end).



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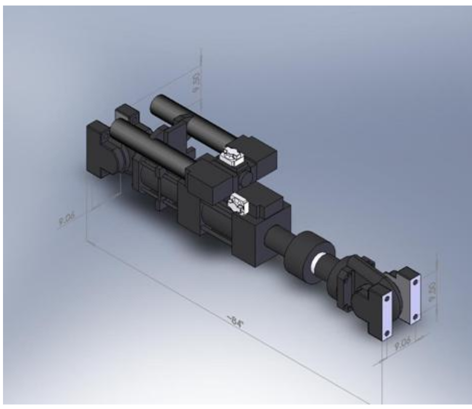
Hydraulic actuators

The two ends of the cylinder (cap and end of the rod) have mounting attachments to connect the cylinder to the object or machine component that it is pushing / pulling. These connections are normally pinned and have the possibility of accommodate rotations.



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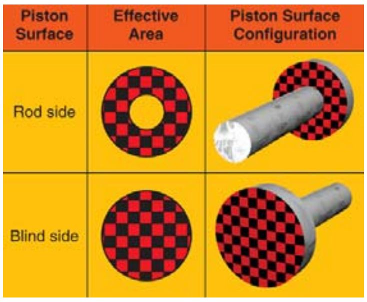
Hydraulic actuators

A hydraulic cylinder is the actuator or "motor" side of this system. The "generator" side of the hydraulic system is the hydraulic pump which brings in a fixed or regulated flow of oil to the hydraulic cylinder, to move the piston. The piston pushes the oil in the other chamber back to the reservoir. If we assume that the oil enters from cap end, during extension stroke, and the oil pressure in the rod end / head end is approximately zero, the force F on the piston rod equals the pressure P in the cylinder times the piston area A: **F = P A**



Hydraulic actuators

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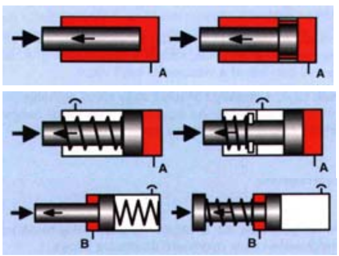
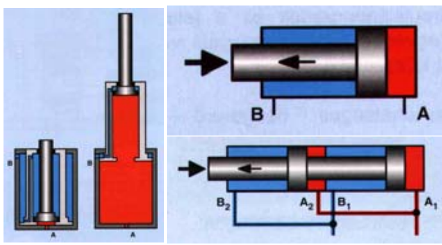
There are several types of linear actuator:

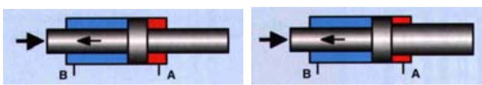
Single-acting:
work can be done only in one direction



Double-acting, single-rod:
work can be done in both directions



Double-acting, double-rod:
work can be done in both directions



Hydraulic actuators

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Single acting cylinders are economical and the simplest design. Hydraulic fluid enters through a port at one end of the cylinder, which extends the rod by means of area difference. An external force or gravity returns the piston rod.

Double acting cylinders have a port at each end, supplied with hydraulic fluid for both the retraction and extension

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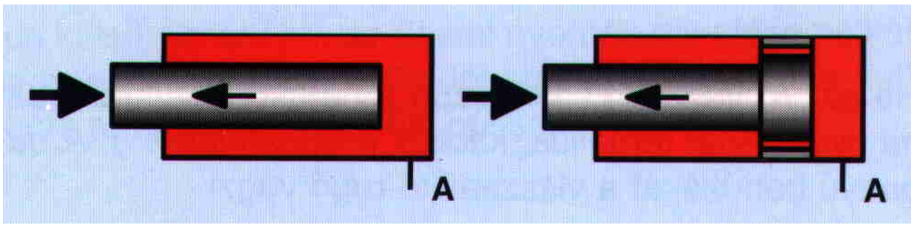
Cylinder types: plunger

smaller force, better efficiency, axial support is necessary but cylinder does not have to be so good quality



Without inner buffer With inner buffer

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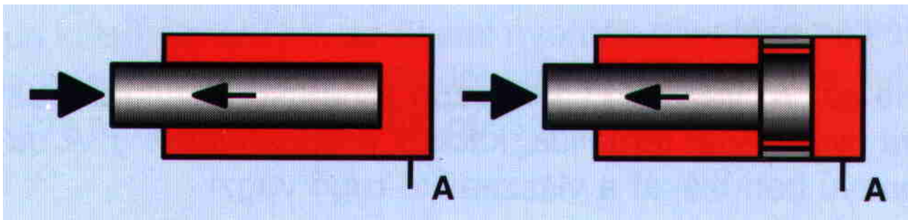
Hydraulic actuators

Cylinder types: plunger

smaller force, better efficiency, axial support is necessary but cylinder does not have to be so good quality

A plunger cylinder can only be used as a pushing cylinder; the maximum force is piston rod area multiplied by pressure. This means that a plunger cylinder in general has a relatively thick piston rod.



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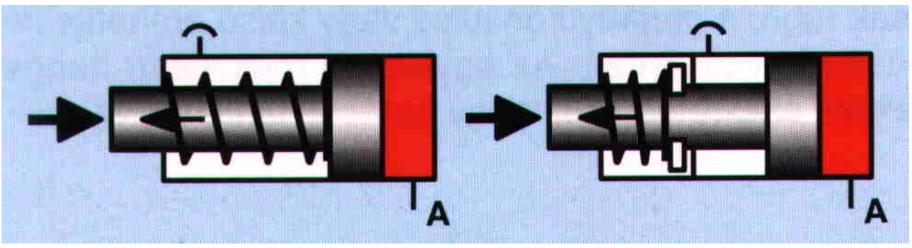
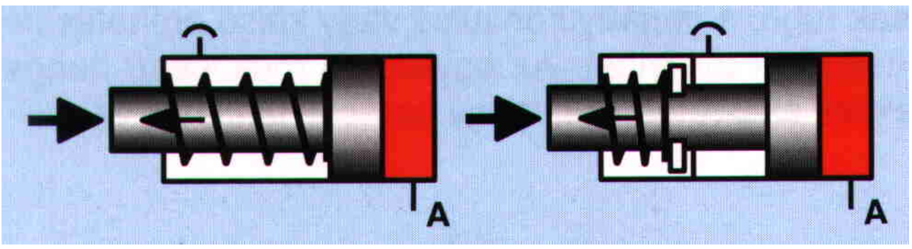
Hydraulic actuators

Cylinder types: piston, single acting, pressing-cylinder and puller



Inside spring　　Outside spring



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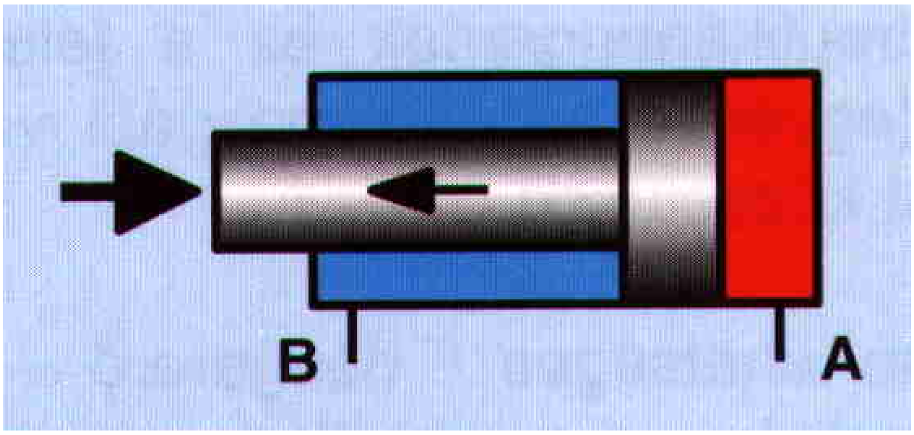
Hydraulic actuators

Cylinder types: piston, double acting

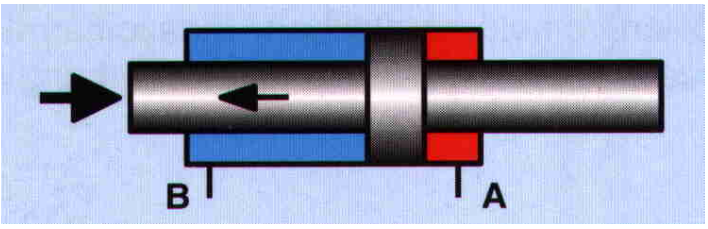
Velocity and force are different in the two direction



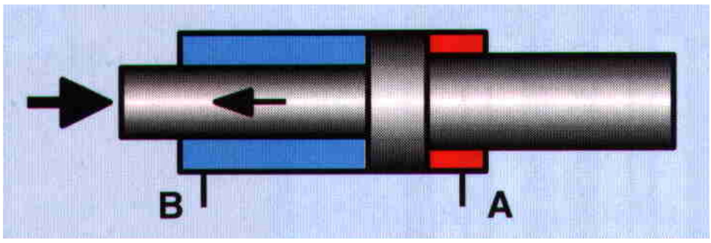
Hydraulic actuators

Cylinder types: piston, double acting, double-rod

Velocity is the same in both directions



Velocity is different in the two directions depending on cross section ratio of the rods

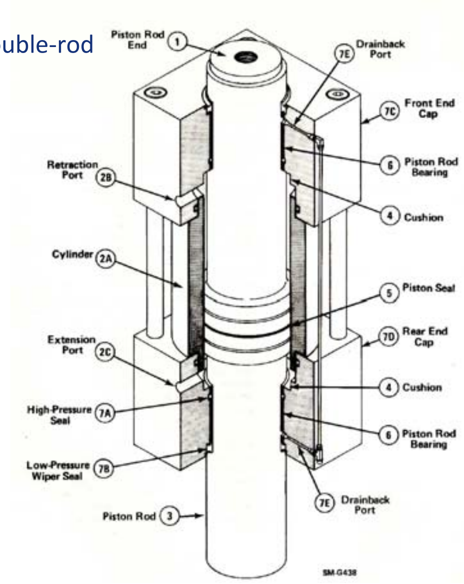


Hydraulic actuators

Cylinder types: piston, double acting, double-rod

This type allows:

- to reduce the distortion;
- to have a symmetric behaviour of the actuator (symmetry of the section);
- to have upper lateral frequencies;
- to have a better control with symmetric servo valve.



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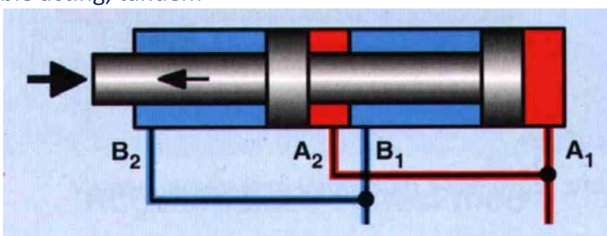
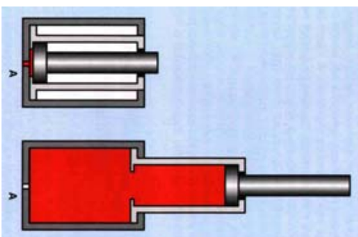
Cylinder types: piston, double acting, tandem

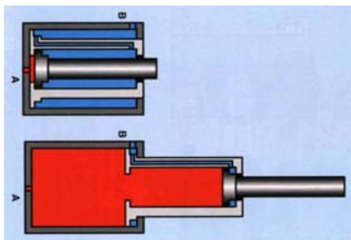
Higher forces



Cylinder types: telescopic, single- and double- acting

Large working paths or limited space





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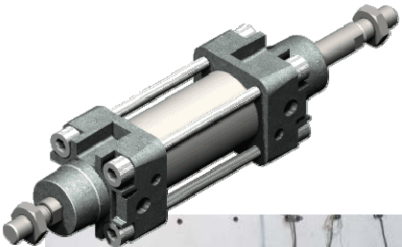
Designs

There are primarily two styles of hydraulic cylinder construction: tie rod style cylinders and welded body style cylinders.

Tie rod cylinder

Tie rod style hydraulic cylinders use high strength threaded steel rods to hold the two end caps to the cylinder barrel. This method of construction is most often seen in industrial factory applications. Small bore cylinders usually have 4 tie rods, while large bore cylinders may require as many as 16 or 20 tie rods in order to retain the end caps under the tremendous forces produced. Tie rod style cylinders can be completely disassembled for service and repair.



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Welded body cylinder

Welded body cylinders have no tie rods. The barrel is welded directly to the end caps. The ports are welded to the barrel. The front rod gland is usually threaded into or bolted to the cylinder barrel. This allows the piston rod assembly and the rod seals to be removed for service.

Welded body cylinders have a number of advantages over tie rod style cylinders. Welded cylinders have a narrower body and often a shorter overall length enabling them to fit better into the tight confines of machinery. Welded cylinders do not suffer from failure due to tie rod stretch at high pressures and long strokes.

The welded design also lends itself to customization. Special features are easily added to the cylinder body. These may include special ports, custom mounts, valve manifolds, and so on.

The smooth outer body of welded cylinders also enables the design of multi-stage telescopic cylinders.

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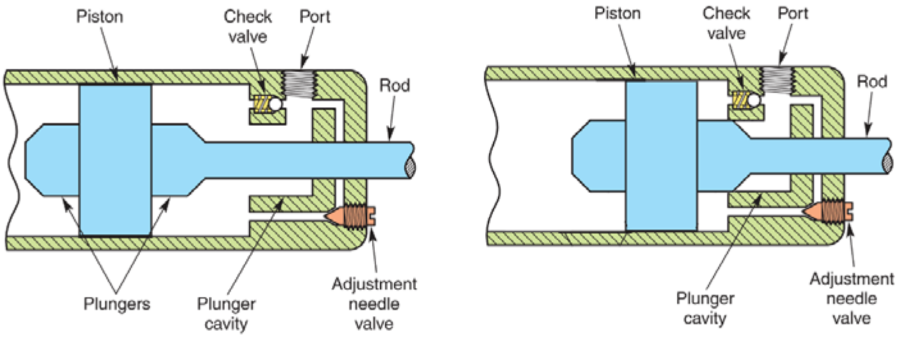
Hydraulic cushions

The actuators have hydraulic cushions. An oil volume is confined between the piston and the cylinder ends and that oil reacts as a damper to reduce impact forces when the piston arrives at full stroke.



Hydraulic actuators

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Hydraulic cushions

The actuators have hydraulic cushions. An oil volume is confined between the piston and the cylinder ends and that oil reacts as a damper to reduce impact forces when the piston arrives at full stroke.

Cylinders often use hydraulic cushions in order to:

- provide a controlled approach to the end of the stroke
- reduces the shock of the impact as the piston contacts the cylinder head.

For this reason the static stroke is always greater than the dynamic stroke.

Hydraulic actuators

Rotary hydraulic actuators

Besides linear actuator mentioned in the previous slides, other actuators are available on the market though their application is less common for civil and seismic testing of structure.

A rotary actuator is an actuator that produces a rotary motion or torque.

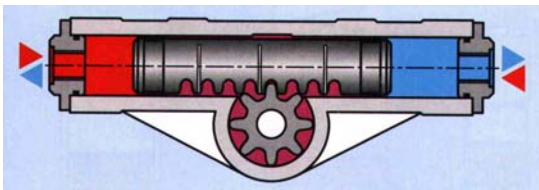
Fluid power rotary actuators are mainly of two common forms:

- those where a linear piston and cylinder mechanism is geared to produce rotation;
- those where a rotating asymmetrical vane swings through a cylinder of two different radii. The differential pressure between the two sides of the vane gives rise to an unbalanced force and thus a torque on the output shaft. Vane actuators require a number of sliding seals and the joins between these seals have tended to cause more problems with leakage than for the piston and cylinder type.

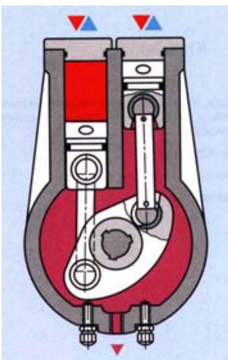
Hydraulic actuators

Rotary hydraulic actuators

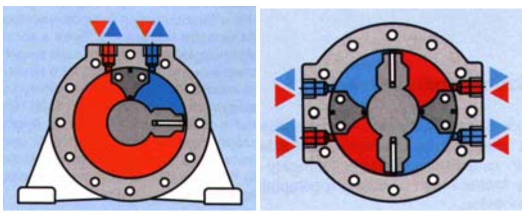
Rack-and-pinion piston-type rotary actuator



Parallel piston rotary actuator



Limited angle rotary actuator



Hydraulic actuators

Check for Buckling

Since the actuators are slender elements working under compression, lateral buckling must be checked. The maximum admissible force can be evaluated according to Euler's approach:

$$F_{max\,L} = \frac{1}{n}\left(\frac{\pi}{L_k}\right)^2 \cdot E \cdot I_1$$

n: safety factor: 1-3,5

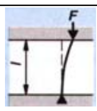
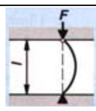
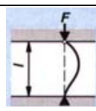
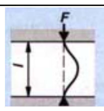
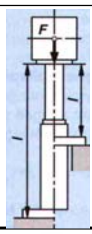
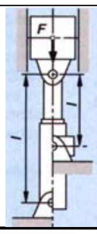
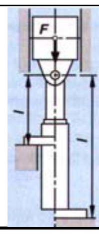
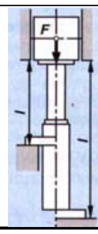
L_k: buckling length

I_1: moment of inertia of the piston rod

E: elasticity modulus of the rod material

Hydraulic actuators

Check for Buckling

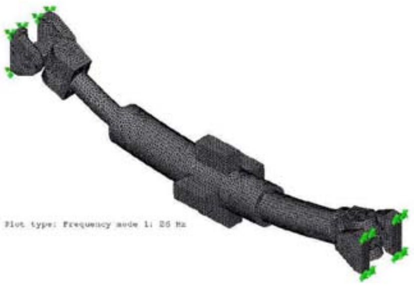
Euler's cases	1. One end free One end fixed or trunnion at end	2. Two ends pivoted and guided	3. One end guided and pivoted, other end fixed	4. Two ends fixed and guided
Picture				
Buckling length	2 L	L	0.707 L	0.5 L
Boundary condition				

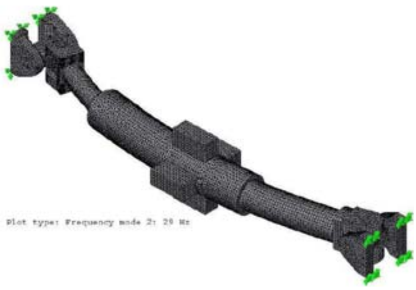
Hydraulic actuators

LATERAL RESONANCE EFFECTS (BOW STRING FREQUENCY)

The lateral resonance issue is a serious factor that has plagued several earthquake simulators (dynamic testing facilities).

All actuators and passive restraining links have a natural lateral resonance often referred to as the 'bow string' resonance due to its modal shape. In designing systems a compromise is struck between actuator stroke and high frequency performance





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OIL COLUMN RESONANCE

For dynamic tests an important issue is represented by the resonant frequency of the oil column.

The oil column resonances are the predominant resonance of the system and typically lie well within the operating frequency range of the system. Using differential pressure and notch filters in the control filters is possible to attenuates these resonances.

The principal effect they have on system sizing is that they mark the point on the performance curve at which the compressibility flow requirements start to have a significant role as opposed to the kinematic flow requirements that dominate at lower frequencies. Oil column resonances also have a crucial impact on system fidelity.

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OIL COLUMN RESONANCE

The resonant frequency of the oil column mainly depends by the following parameters:

- piston area;

- actuator stroke (position of the actuator)

- bulk modulus of oil (influenced by temperature)

- dynamic mass (moving part of the testing equipment + specimen)

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Control theory

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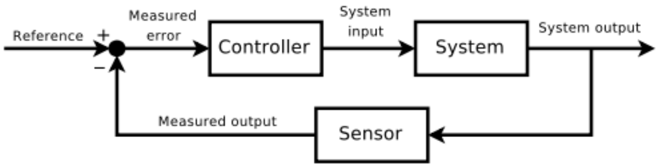
Control theory is an interdisciplinary branch of engineering and mathematics that deals with the behaviour of dynamical systems with inputs. The external input of a system is called the reference. When one or more output variables of a system need to follow a certain reference over time, a controller manipulates the inputs to a system to obtain the desired effect on the output of the system.

The usual objective of a control theory is to calculate solutions for the proper corrective action from the controller that result in system stability, that is, the system will hold the set point and not oscillate around it.

Extensive use is usually made of a diagrammatic style known as the block diagram.



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Control theory

Control theory is a theory that deals with influencing the behaviour of dynamical systems.

Control systems can be thought of as having four functions:

- Measure;
- Compare;
- Compute;
- Correct.

These four functions are completed by five elements:

- Detector;
- Transducer;
- Transmitter;
- Controller;
- Final Control Element.

Control theory

The measuring function is completed by the detector, transducer and transmitter. In practical applications these three elements are typically contained in one unit.

A standard example of a measuring unit is a Resistance thermometer.

The compare and compute functions are completed within the controller which may be completed electronically through a Proportional control, PI Controller, PID Controller, Bistable, Hysteretic control or Programmable logic controller.

The correct function is completed with a final control element. The final control element changes an input or output in the control system which affect the manipulated or controlled variable.

Control theory

Topics in control theory

A number of topics are included in control theory:

- Stability
- Controllability and observability
- Control specification
- Model identification and robustness
  - System identification
  - Analysis
  - Constraints

All these topics are normally considered and analysed for the development of a proper controller.

Control theory

Topics in control theory: Stability

The stability of a general dynamical system with no input can be described with Lyapunov stability criteria. If all solutions of the dynamical system that start out near an equilibrium point X stay near X forever, then X is Lyapunov stable. More strongly, if X is Lyapunov stable and all solutions that start out near converge to X, then X is asymptotically stable.

A linear system that takes an input is called bounded-input bounded-output (BIBO) stable if its output will stay bounded for any bounded input.

Stability for nonlinear systems that take an input is input-to-state stability (ISS), which combines Lyapunov stability and a notion similar to BIBO stability. For simplicity, the following descriptions focus on continuous-time and discrete-time linear systems.

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Topics in control theory: Controllability and observability

Controllability and observability are main issues in the analysis of a system before deciding the best control strategy to be applied, or whether it is even possible to control or stabilize the system.

Controllability is related to the possibility of forcing the system into a particular state by using an appropriate control signal. If a state is not controllable, then no signal will ever be able to control the state. If a state is not controllable, but its dynamics are stable, then the state is termed Stabilizable.

Observability instead is related to the possibility of "observing", through output measurements, the state of a system. If a state is not observable, the controller will never be able to determine the behaviour of an unobservable state and hence cannot use it to stabilize the system. However, similar to the stabilizability condition above, if a state cannot be observed it might still be detectable.

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Topics in control theory: Controllability and observability

From a geometrical point of view, looking at the states of each variable of the system to be controlled, every "bad" state of these variables must be controllable and observable to ensure a good behaviour in the closed-loop system. That is, if one of the eigenvalues of the system is not both controllable and observable, this part of the dynamics will remain untouched in the closed-loop system. If such an eigenvalue is not stable, the dynamics of this eigenvalue will be present in the closed-loop system which therefore will be unstable

Solutions to problems of uncontrollable or unobservable system include adding actuators and sensors.

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Topics in control theory: Control specification

Several different control strategies have been devised in the past years. These vary from extremely general ones (PID controller), to others devoted to very particular classes of systems (especially robotics or aircraft cruise control).

A control problem can have several specifications. Stability, of course, is always present: the controller must ensure that the closed-loop system is stable, regardless of the open-loop stability. A poor choice of controller can even worsen the stability of the open-loop system, which must normally be avoided. Sometimes it would be desired to obtain particular dynamics in the closed loop.

Other "classical" control theory specifications regard the time-response of the closed-loop system: these include the rise time (the time needed by the control system to reach the desired value after a perturbation), peak overshoot (the highest value reached by the response before reaching the desired value) and others (settling time, quarter-decay). Frequency domain specifications are usually related to robustness (see after).

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Topics in control theory: Model identification and robustness

A control system must always have some robustness property. A robust controller is such that its properties do not change much if applied to a system slightly different from the mathematical one used for its synthesis. This specification is important: no real physical system truly behaves like the series of differential equations used to represent it mathematically. Typically a simpler mathematical model is chosen in order to simplify calculations, otherwise the true system dynamics can be so complicated that a complete model is impossible.

System identification

The process of determining the equations that govern the model's dynamics is called system identification. This can be done off-line: for example, executing a series of measures from which to calculate an approximated mathematical model, typically its transfer function. Such identification from the output, however, cannot take account of unobservable dynamics.

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Topics in control theory: Model identification and robustness

System identification

Sometimes the model is built directly starting from known physical equations: for example, in the case of a mass-spring-damper system we know that

Even assuming that a "complete" model is used in designing the controller, all the parameters included in these equations (called "nominal parameters") are never known with absolute precision; the control system will have to behave correctly even when connected to physical system with true parameter values away from nominal.

Some advanced control techniques include an "on-line" identification process. The parameters of the model are calculated ("identified") while the controller itself is running: in this way, if a drastic variation of the parameters ensues (for example, if the robot's arm releases a weight), the controller will adjust itself consequently in order to ensure the correct performance.

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Topics in control theory: Model identification and robustness

Analysis

Analysis of the robustness of a SISO (single input single output) control system can be performed in the frequency domain, considering the system's transfer function and using Nyquist and Bode diagrams. Topics include gain and phase margin and amplitude margin.

For MIMO (multi input multi output) and, in general, more complicated control systems one must consider the theoretical results devised for each control technique: i.e., if particular robustness qualities are needed, the engineer must shift his attention to a control technique by including them in its properties.

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Control theory

Topics in control theory: Model identification and robustness

Constraints

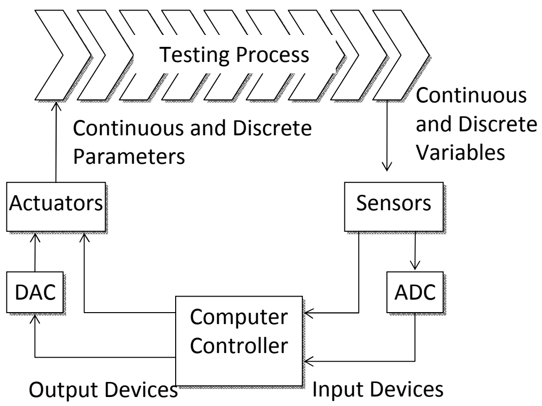
A particular robustness issue is the requirement for a control system to perform properly in the presence of input and state constraints. In the physical world every signal is limited. It could happen that a controller will send control signals that cannot be followed by the physical system: for example, trying to rotate a valve at excessive speed. This can produce undesired behaviour of the closed-loop system, or even damage or break actuators or other subsystems. Specific control techniques are available to solve the problem: model predictive control, and anti-wind up systems. The latter consists of an additional control block that ensures that the control signal never exceeds a given threshold.

Control system

A control system is driving the testing equipment.

To implement process control, the computer must collect data from and transmit signals to the testing equipment.

As shown, several components are required to implement the interface:



Control system

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In control theory, a controller is a device, possibly in the form of a chip, analogue electronics, or computer, which monitors and physically alters the operating conditions of a given dynamical system.

A system can either be described as a MIMO system, having multiple inputs and outputs, therefore requiring more than one controller; or a SISO system, consisting of a single input and single output, hence having only a single controller. Depending on the set-up of the system, adjusting the system's input variable (assuming it is SISO) will affect the operating parameter, otherwise known as the controlled output variable.

Upon receiving the error signal that marks the disparity between the desired value (set-point) and the actual output value, the controller will then attempt to regulate controlled output behaviour. The controller achieves this by either attenuating or amplifying the input signal to the system so that the output is returned to the set-point.

Control system

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In control theory there are two basic types of control. These are feedback and feed-forward.

The input to a feedback controller is the same as what it is trying to control - the controlled variable is "fed back" into the controller.

The thermostat of a house is an example of a feedback controller. This controller relies on measuring the controlled variable, in this case the temperature of the house, and then adjusting the output, whether or not the heater is on. However, feedback control usually results in intermediate periods where the controlled variable is not at the desired set-point. With the thermostat example, if the door of the house were opened on a cold day, the house would cool down. After it fell below the desired temperature (set-point), the heater would kick on, but there would be a period when the house was colder than desired.

Feed-forward control can avoid the slowness of feedback control. With feed-forward control, the disturbances are measured and accounted for before they have time to affect the system.

In the house example, a feed-forward system may measure the fact that the door is opened and automatically turn on the heater before the house can get too cold. The difficulty with feed-forward control is that the effect of the disturbances on the system must be accurately predicted, and there must not be any unmeasured disturbances. For instance, if a window were opened that was not being measured, the feed-forward-controlled thermostat might still let the house cool down.

Control system

To achieve the benefits of feedback control (controlling unknown disturbances and not having to know exactly how a system will respond to disturbances) and the benefits of feed-forward control (responding to disturbances before they can affect the system), there are combinations of feedback and feed-forward that can be used.

Control system

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Within our scope, a control system can be implement as:

- open loop control;
- feed-forward control;
- feedback or close loop control.

Open loop control system

An open loop controller, also called a non-feedback controller, is a type of controller that computes its input into a system using only the current state and its model of the system.

A characteristic of the open-loop controller is that it does not use feedback to determine if its output has achieved the desired goal of the input. This means that the system does not observe the output of the processes that it is controlling. Consequently, a true open-loop system can not engage in machine learning and also cannot correct any errors that it could make. It also may not compensate for disturbances in the system.

Control system

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Open loop control system

Stepper motors are often used for open-loop control of position. A stepper motor rotates to one of a number of fixed positions, according to its internal construction. Sending a stream of electrical pulses to it causes it to rotate by exactly that many steps. Such motors are often used, together with a simple initial datum sensor (a switch that is activated at the machine's home position), for the control of simple robotic machines.

The drawback of open-loop control of steppers is that if the machine load is too high, or the motor attempts to move too quickly, then steps may be skipped. The controller has no means of detecting this and so the machine continues to run slightly out of adjustment, until reset. For this reason, more complex machines incorporate encoders and closed-loop controllers.

The drawback of open-loop control is that it requires perfect knowledge of the system (i.e. one knows exactly what inputs to give in order to get the desired output), and it assumes there are no disturbances to the system.

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Control system

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Feed-forward control

Feed-forward is a term describing an element or pathway within a control system which passes a controlling signal from a source in its external environment, often a command signal from an external operator, to a load elsewhere in its external environment. A control system which has only feed-forward behaviour responds to its control signal in a pre-defined way without responding to how the load reacts; it is in contrast with a system that also has feedback, which adjusts the output to take account of how it affects the load, and how the load itself may vary unpredictably; the load is considered to belong to the external environment of the system.

Some prerequisites are needed for control scheme to be reliable by pure feed-forward without feedback: the external command or controlling signal must be available, and the effect of the output of the system on the load should be known.

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Feed-forward control

Sometimes pure feed-forward control without feedback is called 'ballistic', because once a control signal has been sent, it cannot be further adjusted; any corrective adjustment must be by way of a new control signal. In contrast 'cruise control' adjusts the output in response to the load that it encounters, by a feedback mechanism.

In feed-forward control there is a coupling from the set point and/ or from the disturbance directly to the control variable, that is, a coupling from an input signal to the control variable. The control variable adjustment is not error-based. Instead it is based on knowledge about the process in the form of a mathematical model of the process and knowledge about or measurements of the process disturbances.

The discipline of feed-forward control is seldom practiced due to the difficulty of providing for the mathematical model required to facilitate this type of control. Open-loop control and feedback control, often based on canned PID control algorithms, are much more widely used.

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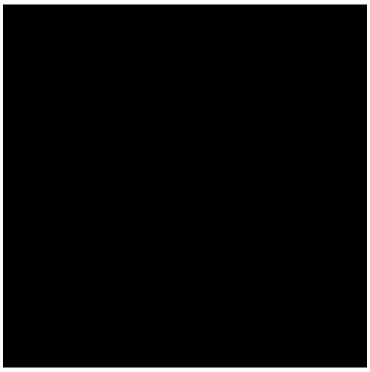
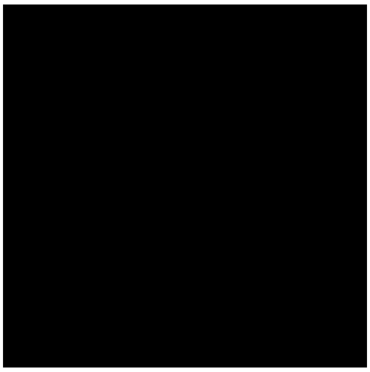
Feed-forward control

Feed-forward control is distinctly different from open loop control systems. Feed-forward control requires a mathematical model of the system being controlled.

Feed-forward control requires integration of the mathematical model into the control algorithm such that it is used to determine the control actions based on what is known about the state of the system being controlled.

[video]





Control system

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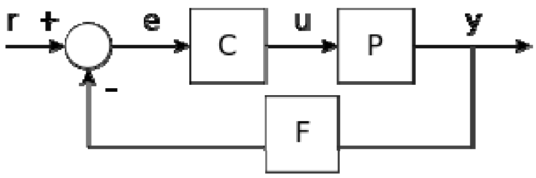
Feedback (close loop) control system

To overcome the limitations of the open-loop controller, control theory introduces feedback.

A closed-loop controller uses feedback to control states or outputs of a dynamical system. Its name comes from the information path in the system: process inputs (e.g., voltage applied to an electric motor) have an effect on the process outputs (e.g., speed or torque of the motor), which is measured with sensors and processed by the controller; the result (the control signal) is "fed back" as input to the process, closing the loop.



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Control system

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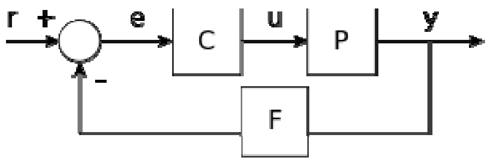
Feedback (close loop) control system



The figure shows the controller C, the plant P and the sensor F.

The output of the system y(t) is fed back through a sensor measurement F to the reference value r(t). The controller C then takes the error e (difference) between the reference and the output to change the inputs u to the system under control P. This kind of controller is a closed-loop controller or feedback controller.

This is called a single-input-single-output (SISO) control system; MIMO (i.e., Multi-Input-Multi-Output) systems, with more than one input/output, are common. In such cases variables are represented through vectors instead of simple scalar values. For some distributed parameter systems the vectors may be infinite-dimensional (typically functions).

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Feedback (close loop) control system

Closed-loop controllers have the following advantages over open-loop controllers:

- disturbance rejection;
- guaranteed performance even with model uncertainties, when the model structure does not match perfectly the real process and the model parameters are not exact;
- unstable processes can be stabilized;
- reduced sensitivity to parameter variations;
- improved reference tracking performance;

In some systems, feedback and feed-forward control are used simultaneously to further improve reference tracking performance.

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Control system

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Feedback (close loop) control system

Feedback is a process in which information about the past or the present influences the same phenomenon in the present or future. As part of a chain of cause-and-effect that forms a circuit or loop, the event is said to "feed back" into itself.

In general, a feedback can be defined as "information about the gap between the actual level and the reference level of a system parameter which is used to alter the gap in some way", emphasizing that the information by itself is not feedback unless translated into action [Ramaprasad, 1983]

Feedback signal - the measurement of the actual level of the parameter of interest.

Feedback loop - the complete causal path that leads from the initial detection of the gap to the subsequent modification of the gap.

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Control system

An example:

Consider a car's cruise control, which is a device designed to maintain vehicle speed at a constant desired or reference speed provided by the driver. The controller is the cruise control, the plant is the car, and the system is the car and the cruise control. The system output is the car's speed, and the control itself is the engine's throttle position which determines how much power the engine generates.

A primitive way to implement cruise control is simply to lock the throttle position when the driver engages cruise control. However, if the cruise control is engaged on a stretch of flat road, then the car will travel slower going uphill and faster when going downhill. This type of controller is called an open-loop controller because no measurement of the system output (the car's speed) is used to alter the control (the throttle position.) As a result, the controller cannot compensate for changes acting on the car, like a change in the slope of the road.

Control system

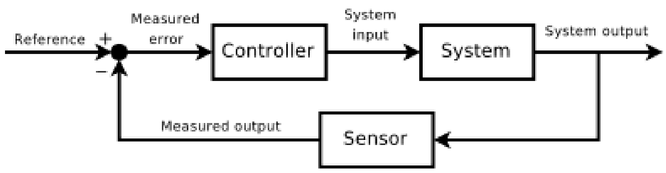
An example:

In a feed-forward control system, a sensor monitor the “disturbance”, i.e. the slope of the road. This measured disturbance together with a mathematical model of the system (car plus the cruise control) allows the controller to act adjusting the input (the throttle position) to maintain the desired output (car’s speed).

In a closed-loop control system, a sensor monitors the system output (the car's speed) and feeds the data to a controller which adjusts the control (the throttle position) as necessary to maintain the desired system output (match the car's speed to the reference speed.) Now when the car goes uphill the decrease in speed is measured, and the throttle position changed to increase engine power, speeding the vehicle. Feedback from measuring the car's speed has allowed the controller to dynamically compensate for changes to the car's speed. It is from this feedback that the paradigm of the control loop arises: the control affects the system output, which in turn is measured and looped back to alter the control.

Control system

Feedback (close loop) control system



Once more, the figure shows the concept of the feedback loop to control the dynamic behaviour of the system: this is negative feedback, because the sensed value is subtracted from the desired value to create the error signal, which is amplified by the controller.

Feedback is extensively used in control theory, using a variety of methods.

The most common general-purpose controller using a control-loop feedback mechanism is a proportional-integral-derivative (PID) controller. Heuristically, the terms of a PID controller can be interpreted as corresponding to time: the proportional term depends on the present error, the integral term on the accumulation of past errors, and the derivative term is a prediction of future error, based on current rate of change.

Control methods

Different control methods can be implemented within the control system in order to obtain the best performances from the testing equipment.

Accuracy of forces and displacement induced by the actuation system to the testing specimen can be achieved only using a proper control method, the complexity of which depends by the complexity of the experimental equipment and the loading history to be adopted for the test execution.

PID controller

A proportional-integral-derivative controller (PID controller) is a generic control loop feedback mechanism (controller) widely used in industrial control systems. A PID controller calculates an "error" value as the difference between a measured process variable and a desired setpoint. The controller attempts to minimize the error by adjusting the process control inputs.

Control methods

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PID controller

The PID controller calculation (algorithm) involves three separate constant parameters, and is accordingly sometimes called three-term control: the proportional, the integral and derivative values, denoted P, I, and D. Heuristically, these values can be interpreted in terms of time: P depends on the present error, I on the accumulation of past errors, and D is a prediction of future errors, based on current rate of change. The weighted sum of these three actions is used to adjust the process via a control element such as the position of a control valve.

In the absence of knowledge of the underlying process, a PID controller has historically been considered to be the best controller. By tuning the three parameters in the PID controller algorithm, the controller can provide control action designed for specific process requirements. The response of the controller can be described in terms of the responsiveness of the controller to an error, the degree to which the controller overshoots the setpoint and the degree of system oscillation. Note that the use of the PID algorithm for control does not guarantee optimal control of the system or system stability.

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Control methods

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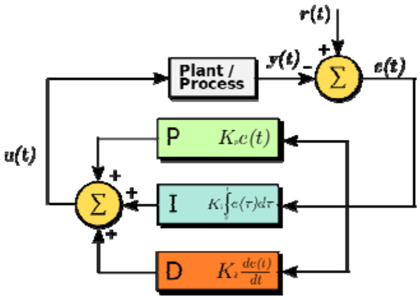
PID controller

Some applications may require using only one or two actions to provide the appropriate system control. This is achieved by setting the other parameters to zero. A PID controller will be called a PI, PD, P or I controller in the absence of the respective control actions. PI controllers are fairly common, since derivative action is sensitive to measurement noise, whereas the absence of an integral term may prevent the system from reaching its target value due to the control action.



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Control methods

PID controller

An example:

A familiar example of a control loop is the action taken when adjusting hot and cold faucets (valves) to maintain the water at a desired temperature. This typically involves the mixing of two process streams, the hot and cold water. The person touches the water to sense or measure its temperature. Based on this feedback they perform a control action to adjust the hot and cold water valves until the process temperature stabilizes at the desired value.

The sensed water temperature is the process variable or process value (PV). The desired temperature is called the setpoint (SP). The input to the process (the water valve position) is called the manipulated variable (MV). The difference between the temperature measurement and the setpoint is the error (e) and quantifies whether the water is too hot or too cold and by how much.

Control methods

PID controller

An example:

After measuring the temperature (PV), and then calculating the error, the controller decides when to change the tap position (MV) and by how much. When the controller first turns the valve on, it may turn the hot valve only slightly if warm water is desired, or it may open the valve all the way if very hot water is desired. This is an example of a simple proportional control. In the event that hot water does not arrive quickly, the controller may try to speed-up the process by opening up the hot water valve more-and-more as time goes by. This is an example of an integral control.

Making a change that is too large when the error is small is equivalent to a high gain controller and will lead to overshoot. If the controller were to repeatedly make changes that were too large and repeatedly overshoot the target, the output would oscillate around the setpoint in either a constant, growing, or decaying sinusoid. If the oscillations increase with time then the system is unstable, whereas if they decrease the system is stable. If the oscillations remain at a constant magnitude the system is marginally stable.

Control methods

PID controller

An example:

In the interest of achieving a gradual convergence at the desired temperature (SP), the controller may wish to damp the anticipated future oscillations. So in order to compensate for this effect, the controller may elect to temper its adjustments. This can be thought of as a derivative control method.

If a controller starts from a stable state at zero error (PV = SP), then further changes by the controller will be in response to changes in other measured or unmeasured inputs to the process that impact on the process, and hence on the PV. Variables that impact on the process other than the MV are known as disturbances. Generally controllers are used to reject disturbances and/or implement setpoint changes. In this example, changes in feedwater temperature constitute a disturbance to the faucet temperature control process.

In theory, a controller can be used to control any process which has a measurable output (PV), a known ideal value for that output (SP) and an input to the process (MV) that will affect the relevant PV. Controllers are used in industry to regulate temperature, pressure, flow rate, chemical composition, speed and practically every other variable for which a measurement exists.

Control methods

PID controller theory

The PID control scheme is named after its three correcting terms, whose sum constitutes the manipulated variable (MV). The proportional, integral, and derivative terms are summed to calculate the output of the PID controller. Defining u(t) as the controller output, the final form of the PID algorithm is:

$$u(t) = MV(t) = K_p e(t) + K_i \int_0^t e(\tau)\,d\tau + K_d \frac{d}{dt} e(t)$$

Where:

Kp: Proportional gain;

Ki: integral gain;

Kd: derivative gain

e: error = setpoint – process variable (ST-PV);

t: time or instantaneous time

τ: variable of integration ranging from time 0 to the present t.

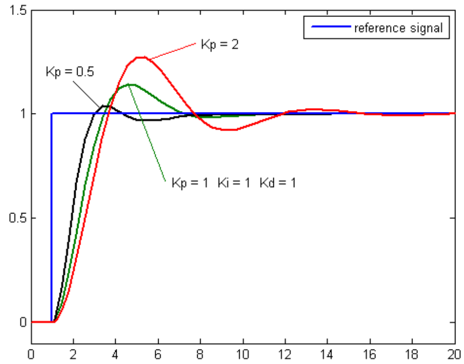
Control methods

PID controller theory: Proportional term

The proportional term produces an output value that is proportional to the current error value. The proportional response can be adjusted by multiplying the error by a constant Kp, called the proportional gain constant.

$$P_{out} = K_p e(t)$$

A high proportional gain results in a large change in the output for a given change in the error. If the proportional gain is too high, the system can become unstable. In contrast, a small gain results in a small output response to a large input error, and a less responsive or less sensitive controller. If the proportional gain is too low, the control action may be too small when responding to system disturbances.



Control methods

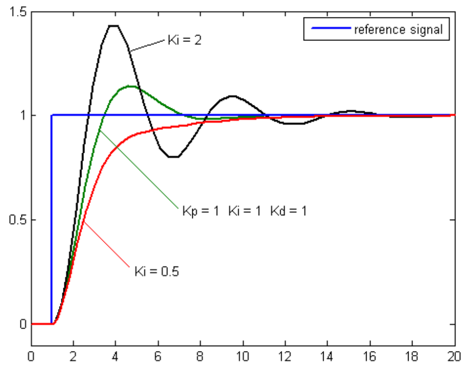
PID controller theory: Integral term

The contribution from the integral term is proportional to both the magnitude of the error and the duration of the error. The integral in a PID controller is the sum of the instantaneous error over time and gives the accumulated offset that should have been corrected previously.

$$I_{out} = K_i \int_0^t e(\tau) d\tau$$

The integral term accelerates the movement of the process towards setpoint and eliminates the residual steady-state error that occurs with a pure proportional controller.

However, since the integral term responds to accumulated errors from the past, it can cause the present value to overshoot the setpoint value.



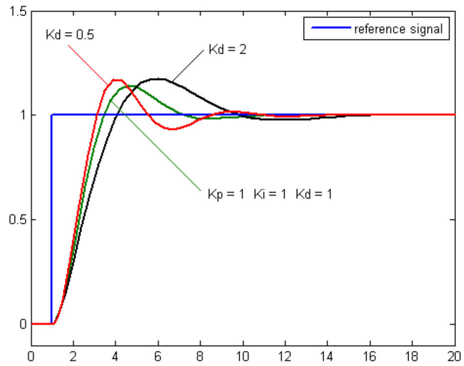
Control methods

PID controller theory: Derivative term

The derivative of the process error is calculated by determining the slope of the error over time and multiplying this rate of change by the derivative gain Kd. The magnitude of the contribution of the derivative term to the overall control action is termed the derivative gain, Kd.

$$D_{out} = K_d \frac{d}{dt} e(t)$$

Derivative action predicts system behaviour and thus improves settling time and stability of the system



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Control methods

PID controller theory: Tuning

Tuning of a control loop is the adjustment of its control parameters to the optimum values for the desired control response. Stability (bounded oscillation) is a basic requirement, but beyond that, different systems have different behaviour, different applications have different requirements, and requirements may conflict with one another.

PID tuning is a difficult problem, even though there are only three parameters and in principle is simple to describe, because it must satisfy complex criteria within the limitations of PID control. There are accordingly various methods for loop tuning, and more sophisticated techniques are the subject of patents.

Designing and tuning a PID controller appears to be conceptually intuitive, but can be hard in practice, if multiple (and often conflicting) objectives such as short transient and high stability are to be achieved. Usually, initial designs need to be adjusted repeatedly through computer simulations until the closed-loop system performs or compromises as desired.

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Control methods

PID controller theory: Tuning

Some processes have a degree of nonlinearity and so parameters that work well at full-load conditions don't work when the process is starting up from no-load; this can be corrected by gain scheduling (using different parameters in different operating regions). PID controllers often provide acceptable control using default tunings, but performance can generally be improved by careful tuning, and performance may be unacceptable with poor tuning.

Stability: If the PID controller parameters are chosen incorrectly, the controlled process input can be unstable, i.e., its output diverges, with or without oscillation, and is limited only by saturation or mechanical breakage. Instability is caused by excess gain, particularly in the presence of significant lag.

Generally, stabilization of response is required and the process must not oscillate for any combination of process conditions and setpoints, though sometimes marginal stability (bounded oscillation) is acceptable or desired.

Control methods

PID controller theory: Tuning

Optimum behaviour: The optimum behaviour on a process change or setpoint change varies depending on the application.

Two basic requirements are regulation (disturbance rejection – staying at a given setpoint) and command tracking (implementing setpoint changes) – these refer to how well the controlled variable tracks the desired value. Specific criteria for command tracking include rise time and settling time. Some processes must not allow an overshoot of the process variable beyond the setpoint if, for example, this would be unsafe. Other processes must minimize the energy expended in reaching a new setpoint.

Control methods

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PID controller theory: Tuning

Tuning methods: There are several methods for tuning a PID loop. The most effective methods generally involve the development of some form of process model, then choosing P, I, and D based on the dynamic model parameters. Manual tuning methods can be relatively inefficient, particularly if the loops have response times on the order of minutes or longer.

The choice of method will depend largely on whether or not the loop can be taken "offline" for tuning, and on the response time of the system. If the system can be taken offline, the best tuning method often involves subjecting the system to a step change in input, measuring the output as a function of time, and using this response to determine the control parameters.

Control methods

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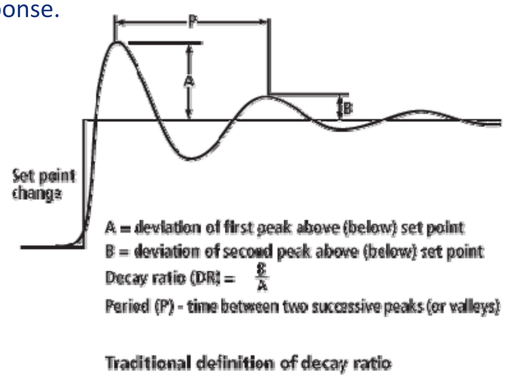
PID controller theory: Tuning

Manual method: If the system must remain online, one tuning method is to first set Ki and Kd values to zero. Increase the Kp until the output of the loop oscillates, then the Kp should be set to approximately half of that value for a "quarter amplitude decay" type response.



Control methods

PID controller theory: Tuning

Manual method: If the system must remain online, one tuning method is to first set Ki and Kd values to zero. Increase the Kp until the output of the loop oscillates, then the Kp should be set to approximately half of that value for a "quarter amplitude decay" type response.

Then increase Ki until any offset is corrected in sufficient time for the process. However, too much Ki will cause instability.

Finally, increase Kd, if required, until the loop is acceptably quick to reach its reference after a load disturbance. However, too much Kd will cause excessive response and overshoot.

A fast PID loop tuning usually overshoots slightly to reach the setpoint more quickly; however, some systems cannot accept overshoot, in which case an over-damped closed-loop system is required, which will require a Kp setting significantly less than half that of the Kp setting that was causing oscillation.

Control methods

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PID controller theory: Tuning

Manual method: **EFFECTS OF INCREASING A PARAMETER INDEPENDENTLY**

Parameter	Rise time	Overshoot	Settling time	Steady-state error	Stability
Kp	Decrease	Increase	Small change	Decrease	Degrade
Ki	Decrease	Increase	Increase	Eliminate	Degrade
Kd	Minor change	Decrease	Decrease	No effect in theory	Improve if Kd is small

Control methods

PID controller theory: Tuning

Ziegler–Nichols method: Another tuning method is formally known as the Ziegler–Nichols method, introduced by John G. Ziegler and Nathaniel B. Nichols in the 1940s. As for the manual tuning, the Ki and Kd gains are first set to zero. The P gain is increased until it reaches the ultimate gain, Ku, at which the output of the loop starts to oscillate. Ku and the oscillation period Pu are used to set the gains as shown:

Control type	Kp	Ki	Kd
P	0.50 Ku	-	-
PI	0.45 Ku	1.2 Kp / Pu	-
PID	0.60 Ku	2.0 Kp / Pu	Kp Pu / 8

These gains apply to the ideal, parallel form of the PID controller. When applied to the standard PID form, the integral and derivative time parameters Ti and Td are only dependent on the oscillation period Pu.

Control methods

PID modifications

Some minor modifications to the PID control loop can be applied to improve its behaviour and response.

Integral windup

One common problem resulting from the ideal PID implementations is integral windup, where a large change in setpoint occurs (say a positive change) and the integral term accumulates an error larger than the maximal value for the regulation variable (windup), thus the system overshoots and continues to increase as this accumulated error is unwound. This problem can be addressed by:

- Initializing the controller integral to a desired value
- Increasing the setpoint in a suitable ramp
- Disabling the integral function until the PV has entered the controllable region
- Preventing the integral term from accumulating above or below pre-determined bounds

Control methods

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PID modifications

Overshooting from known disturbances

A disturbance can affect a process stabilised by a PID control loop influencing the process variable (PV). The integral function of the controller tends to compensate this error by introducing another error in the opposite direction. This overshoot can be avoided by freezing of the integral function after the recognising the disturbance for the time the control loop typically needs to reach the setpoint of the PV.

Replacing the integral function by a model based part

Often the time-response of the system is approximately known. Then it is an advantage to simulate this time-response with a model and to calculate some unknown parameter from the actual response of the system.

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Control methods

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PID modifications

PI controller

A PI Controller (proportional-integral controller) is a special case of the PID controller in which the derivative (D) of the error is not used.

The lack of derivative action may make the system more steady in the steady state in the case of noisy data. This is because derivative action is more sensitive to higher-frequency terms in the inputs.

Without derivative action, a PI-controlled system is less responsive to real (non-noise) and relatively fast alterations in state and so the system will be slower to reach setpoint and slower to respond to perturbations than a well-tuned PID system may be.

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PID modifications

Deadband

Many PID loops control a mechanical device (e.g. a valve, as in our case). Mechanical maintenance can be a major cost and wear leads to control degradation in the form of either static friction or a deadband in the mechanical response to an input signal. The rate of mechanical wear is mainly a function of how often a device is activated to make a change. Where wear is a significant concern, the PID loop may have an output deadband to reduce the frequency of activation of the output (valve). This is accomplished by modifying the controller to hold its output steady if the change would be small (within the defined deadband range). The calculated output must leave the deadband before the actual output will change.

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Control methods

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PID modifications

Setpoint step change

The proportional and derivative terms can produce excessive movement in the output when a system is subjected to an instantaneous step increase in the error, such as a large setpoint change. In the case of the derivative term, this is due to taking the derivative of the error, which is very large in the case of an instantaneous step change. As a result, some PID algorithms incorporate the following modifications:

- Derivative of the process variable
- Setpoint ramping
- Setpoint weighting

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Control methods

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PID modifications

Setpoint step change

The proportional and derivative terms can produce excessive movement in the output when a system is subjected to an instantaneous step increase in the error, such as a large setpoint change. In the case of the derivative term, this is due to taking the derivative of the error, which is very large in the case of an instantaneous step change. As a result, some PID algorithms incorporate the following modifications:

- **Derivative of the process variable**

  In this case the PID controller measures the derivative of the measured process variable (PV), rather than the derivative of the error. This quantity is always continuous (i.e., never has a step change as a result of changed setpoint). For this technique to be effective, the derivative of the PV must have the opposite sign of the derivative of the error, in the case of negative feedback control.

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Control methods

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PID modifications

Setpoint step change

The proportional and derivative terms can produce excessive movement in the output when a system is subjected to an instantaneous step increase in the error, such as a large setpoint change. In the case of the derivative term, this is due to taking the derivative of the error, which is very large in the case of an instantaneous step change. As a result, some PID algorithms incorporate the following modifications:

- **Setpoint ramping**

  In this modification, the setpoint is gradually moved from its old value to a newly specified value using a linear or first order differential ramp function. This avoids the discontinuity present in a simple step change.

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Control methods

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PID modifications

Setpoint step change

The proportional and derivative terms can produce excessive movement in the output when a system is subjected to an instantaneous step increase in the error, such as a large setpoint change. In the case of the derivative term, this is due to taking the derivative of the error, which is very large in the case of an instantaneous step change. As a result, some PID algorithms incorporate the following modifications:

- **Setpoint weighting**

  Setpoint weighting uses different multipliers for the error depending on which element of the controller it is used in. The error in the integral term must be the true control error to avoid steady-state control errors. This affects the controller's setpoint response. These parameters do not affect the response to load disturbances and measurement noise.

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Control methods

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Limitations of PID controller

While PID controllers are applicable to many control problems, and often perform satisfactorily without any improvements or even tuning, they can perform poorly in some applications, and do not in general provide optimal control. The fundamental difficulty with PID control is that it is a feedback system, with constant parameters, and no direct knowledge of the process, and thus overall performance is reactive and a compromise – while PID control is the best controller with no model of the process, better performance can be obtained by incorporating a model of the process.

The most significant improvement is to incorporate feed-forward control with knowledge about the system, and using the PID only to control error. Alternatively, PID controllers can be modified in more minor ways, such as by changing the parameters (either gain scheduling in different use cases or adaptively modifying them based on performance), improving measurement (higher sampling rate, precision, and accuracy, and low-pass filtering if necessary), or cascading multiple PID controllers.

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Control methods

Limitations of PID controller

PID controllers, when used alone, can give poor performance when the PID loop gains must be reduced so that the control system does not overshoot, oscillate or hunt about the control setpoint value.

They also :

- have difficulties in the presence of non-linearities,
- may trade-off regulation versus response time,
- do not react to changing process behaviour (say, the process changes after it has warmed up),
- have lag in responding to large disturbances.

Control methods

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Limitations of PID controller

Linearity (and symmetry)

Another problem faced with PID controllers is that they are linear, and in particular symmetric. Thus, performance of PID controllers in non-linear systems is variable. Problems can arise when the process can be controlled just in one direction: in this case overshoot can only be corrected slowly. In this case the PID should be tuned to be over-damped, to prevent or reduce overshoot, though this reduces performance (it increases settling time).

As an example, in temperature control, a common use case is active heating (via a heating element) but passive cooling (heating off, but no cooling), so overshoot can only be corrected slowly since the temperature cannot be forced downward.

Control methods

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Limitations of PID controller

Noise in derivative

A problem with the derivative term is that small amounts of measurement or process noise can cause large amounts of change in the output. It is often helpful to filter the measurements with a low-pass filter in order to remove higher-frequency noise components. However, low-pass filtering and derivative control can cancel each other out, so reducing noise by instrumentation is a much better choice. Alternatively, a nonlinear median filter may be used, which improves the filtering efficiency and practical performance. In some case, the differential band can be turned off in many systems with little loss of control. This is equivalent to using the PID controller as a PI controller.

Control methods

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Improvements of PID controller

Feed-forward

The performance of the control system can be improved by combining the feedback (or closed-loop) control of a PID controller with feed-forward control. Knowledge about the system (such as the desired acceleration and inertia) can be fed forward and combined with the PID output to improve the overall system performance. The feed-forward value alone can often provide the major portion of the controller output. The PID controller can be used primarily to respond to whatever difference or error remains between the setpoint (SP) and the actual value of the process variable (PV). Since the feed-forward output is not affected by the process feedback, it can never cause the control system to oscillate, thus improving the system response and stability.

Control methods

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Improvements of PID controller

Feed-forward

An example: in most motion control systems, in order to accelerate a mechanical load under control, more force or torque is required from the prime mover, motor, or actuator. If a velocity loop PID controller is being used to control the speed of the load and command the force or torque being applied by the prime mover, then it is beneficial to take the instantaneous acceleration desired for the load, scale that value appropriately and add it to the output of the PID velocity loop controller.

This means that whenever the load is being accelerated or decelerated, a proportional amount of force is commanded from the prime mover regardless of the feedback value. The PID loop in this situation uses the feedback information to change the combined output to reduce the remaining difference between the process setpoint and the feedback value. Working together, the combined open-loop feed-forward controller and closed-loop PID controller can provide a more responsive, stable and reliable control system.

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Improvements of PID controller

Other improvements

In addition to feed-forward, PID controllers are often enhanced through methods such as:

- PID gain scheduling (changing parameters in different operating conditions);
- fuzzy logic;
- computational verb logic.

Further practical application issues can arise from instrumentation connected to the controller. A high enough sampling rate, measurement precision, and measurement accuracy are required to achieve adequate control performance.

Another new method for improvement of PID controller is to increase the degree of freedom by using fractional order. The order of the integrator and differentiator add increased flexibility to the controller.

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Cascade PID controller

One distinctive advantage of PID controllers is that two PID controllers can be used together to yield better dynamic performance. This is called cascaded PID control. In cascade control there are two PID controllers arranged with one PID controlling the setpoint of another.

A PID controller acts as outer loop controller, which controls the primary physical parameter, such as fluid level or velocity. The other controller acts as inner loop controller, which reads the output of outer loop controller as setpoint, usually controlling a more rapid changing parameter, flowrate or acceleration. It can be mathematically proven that the working frequency of the controller is increased and the time constant of the object is reduced by using cascaded PID controller.

Electrical actuation systems

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As an alternative to hydraulic actuation system, electrical actuation system can be used.

In this case the whole system is simpler with respect to the hydraulic case:

HYDRAULIC Actuation	ELECTRICAL Actuation
- hydraulic power system;	- electrical power system;
- accumulators;	
- piping system;	- electrical connections;
- manifolds;	
- servo valves;	
- actuators (or jacks);	- actuators (or jacks);
- controllers and associated sensors.	- controllers and associated sensors.

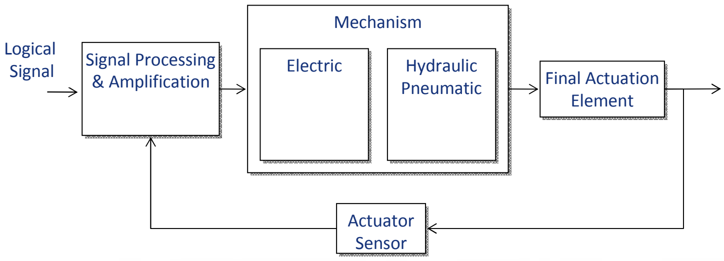
Electrical actuation systems

As for the hydraulic actuators, also the electrical ones are hardware devices that convert a controller command signal into a change in a physical parameter.

The change is usually mechanical (e.g., position or velocity).

An actuator is also a transducer because it changes one type of physical quantity into some alternative form.

An actuator is usually activated by a low-level command signal, so an amplifier may be required to provide sufficient power to drive the actuator.



Electrical actuators

Type of actuators:

- Electro-dynamic shaker
- Electrical actuators (Screw jacks)
  - Lead screw
  - Ball screw
  - Roller screw
- Electric motors
  - DC servomotors
  - AC motors
  - Stepper motors
- Solenoids

Electro dynamic shakers

Some large shakers allow providing static load support up to 5000 kg.

The addition of a slip table extends its capabilities.

The biggest performances are about:

- useful frequency range for vibration control from 5 to 2500 Hz
- up to ± 25 mm displacement
- maximum vibration force about 150 kN
- mono-axial excitation
- multi-axial excitation combining more devices

Electro dynamic shakers

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Advantages

- Large frequency range of excitation and specially at very high frequency (up to 2000 Hz),
- Low distortion.

Disadvantages

- Very low stroke (dew centimetres);
- Does not run at very low frequency (under 2 or 5 Hz);
- Important volume or size;
- Very expensive;
- Limited forces;
- Limited static load compensation.

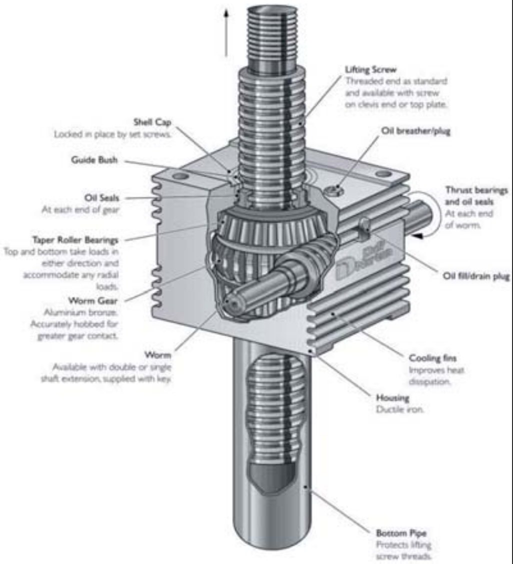
Lead screw jacks

Some of the electrical actuator operates using a screw jack.

A screw jack is a type of jack which is operated by turning a lead-screw.

An advantage of jackscrews over some other types of jack is that they are self-locking, which means when the rotational force on the screw is removed, it will remain motionless where it was left and will not rotate backwards, regardless of how much load it is supporting.

This makes them inherently safer than hydraulic jacks, for example, which will move backwards under load if the force on the hydraulic actuator is accidentally released.



Lead screw jacks

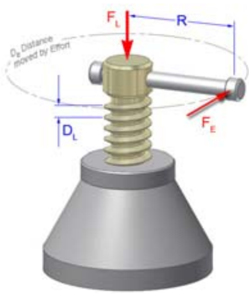
The mechanical advantage of a screw jack, the ratio of the force the jack exerts on the load to the input force on the lever, ignoring friction, is

$$\frac{F_L}{F_E} = \frac{2\pi R}{D_L}$$

where

- F_L is the force the jack exerts on the load
- F_E is the rotational force exerted on the handle of the jack
- R is the length of the jack handle, from the screw axis to where the force is applied
- D_L is the lead of the screw.

However, most screw jacks have large amounts of friction which increase the input force necessary, so the actual mechanical advantage is often only 30% to 50% of this figure.



Ball screw actuators

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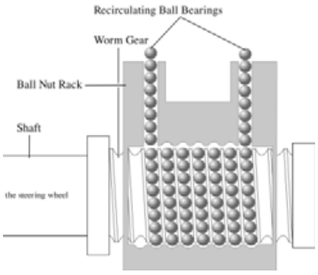
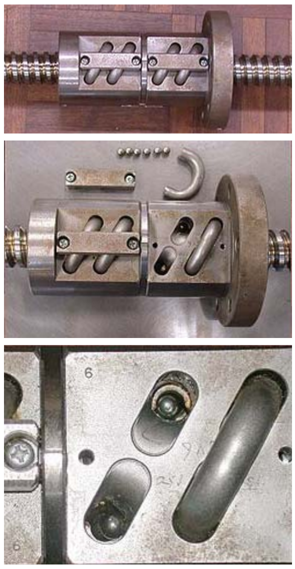
A ball screw is a mechanical linear actuator that translates rotational motion to linear motion with little friction.
A threaded shaft provides a helical raceway for ball bearings which act as a precision screw.

As well as being able to apply or withstand high thrust loads, they can do so with minimum internal friction.





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Ball screw actuators

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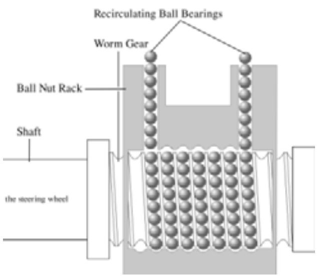
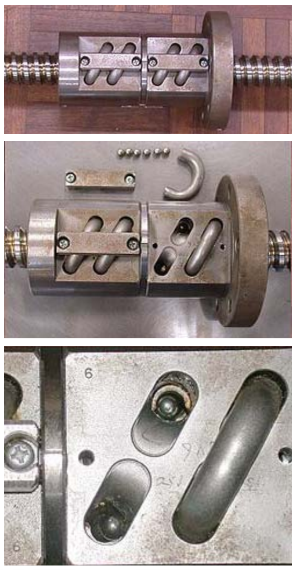
They are made to close tolerances and are therefore suitable for use in situations in which high precision is necessary.

The ball assembly acts as the nut while the threaded shaft is the screw. In contrast to conventional lead screws, ball screws tend to be rather bulky, due to the need to have a mechanism to re-circulate the balls.





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Ball screw actuators

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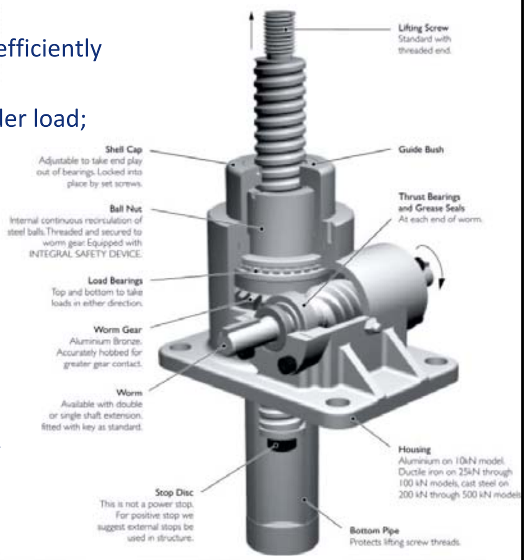
Advantages

- Move loads and apply forces more efficiently than other mechanical actuators;
- Faster operation and longer life under load;
- Require less power;
- Permit synchronisation of multiple units;
- Capacity from 10 kN to 500 kN;
- Handles full load in tension or compression

Disadvantages

- Can be back-driven due to their low internal friction
- Cost.



Roller screw actuators

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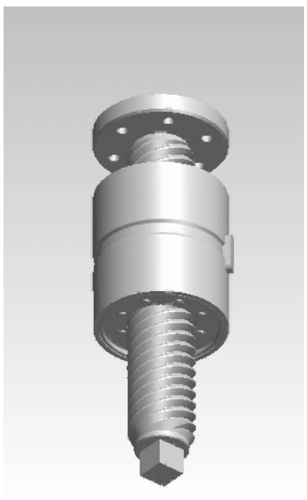
A roller screw, also known as a planetary roller screw or satellite roller screw, is a low-friction precision screw-type actuator.

Planetary roller screws are used as the actuating mechanism in many electro-mechanical linear actuators. Due to its complexity the roller screw is a relatively expensive actuator (as much as an order of magnitude more expensive than ball screws), but may be suitable for high-precision, high-speed, heavy-load, long-life and heavy-use applications.

Roller screw mechanisms are commonly incorporated into motion/positioning systems in a variety of industries such as manufacturing and aerospace.



Roller screw actuators

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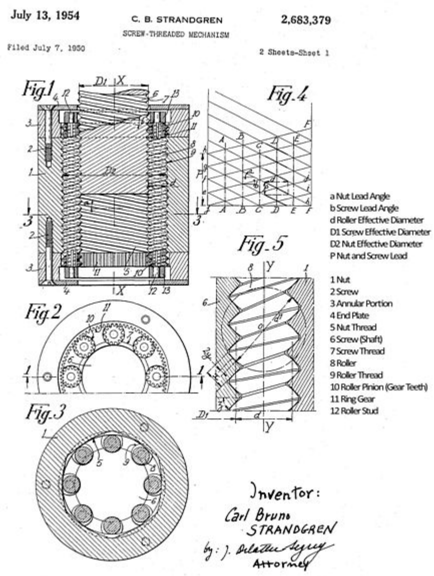
The three main elements of a typical planetary roller screw are the screw shaft, nut and planetary roller. The screw, a shaft with a multi-start V-shaped thread, provides a helical raceway for multiple rollers radially arrayed around the screw and encapsulated by a threaded nut. The thread of the screw is typically identical to the internal thread of the nut. The rollers spin in contact with, and serve as low-friction transmission elements between screw and nut.

As with a lead screw or ball screw, rotation of the nut results in screw travel, and rotation of the screw results in nut travel.



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Roller screw actuators

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A roller screw is a mechanical actuator similar to a ball screw that uses rollers as the load transfer elements between nut and screw instead of balls.

Providing more bearing points than ball screws within a given volume, roller screws can be more compact for a given load capacity while providing similar efficiency (75%-90%) at low to moderate speeds, and maintain relatively high efficiency at high speeds.

Roller screws can surpass ball screws in regard to positioning precision, load rating, rigidity, speed, acceleration, and lifetime. Standard roller screw actuators can achieve dynamic load ratings above 130 tons of force (exceeded in single-unit actuator capacity only by hydraulic cylinders).

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Electric motors

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Different types of motors can be used to operate the electrical actuators.
In the next slides, distinction will be done between:

- DC motors
  - brushed DC motors;
  - brushless DC motors;
  - stepper motors;
- AC motors
  - induction or asynchronous motors;
  - synchronous motors;
- Servomotors

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DC motors

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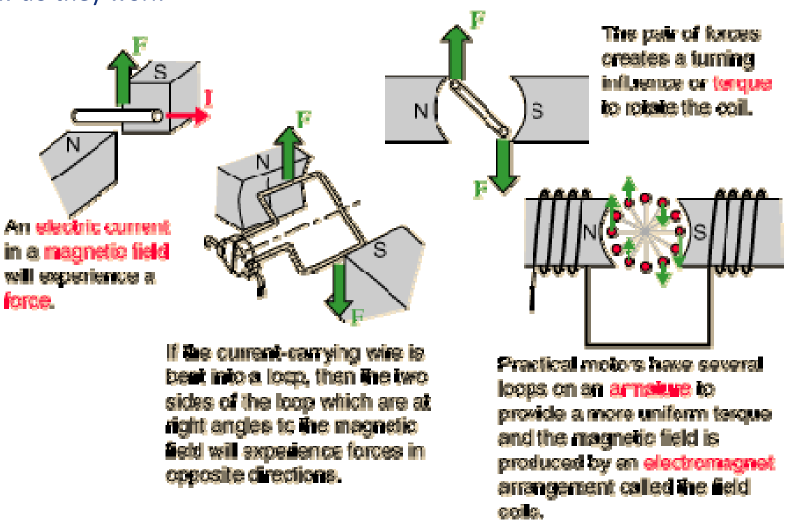
How do they work



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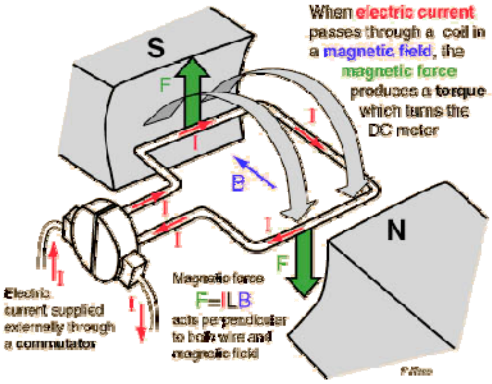
DC motors

A DC motor is a mechanically commutated electric motor powered from direct current (DC). The stator is stationary in space by definition and therefore its current. The current in the rotor is switched by the commutator to also be stationary in space. This is how the relative angle between the stator and rotor magnetic flux is maintained near 90 degrees, which generates the maximum torque.

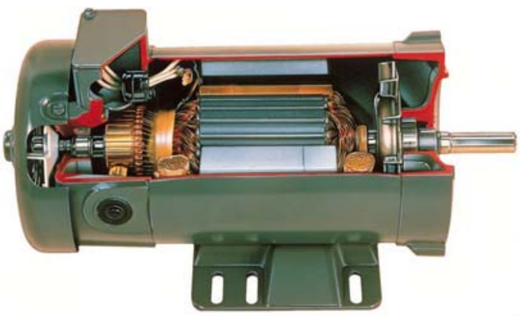
DC motors have;
- a rotating armature winding (winding in which a voltage is induced) but non-rotating armature magnetic field;
- a static field winding (winding that produce the main magnetic flux) or permanent magnet.



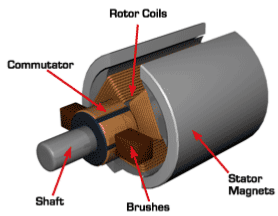
DC motors

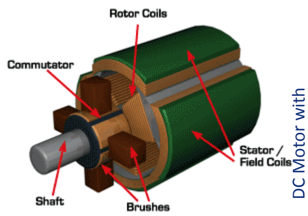
The speed of a DC motor can be controlled by changing the voltage applied to the armature or by changing the field current. The introduction of variable resistance in the armature circuit or field circuit allowed speed control.

Modern DC motors are often controlled by power electronics systems called DC drives.



DC motor, field structure, and armature assembly. (Courtesy Reliance Electric Co.)





Brushed DC motors

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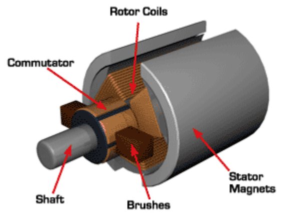
The brushed DC electric motor generates torque directly from DC power supplied to the motor by using internal commutation, stationary magnets (permanent or electromagnets), and rotating electrical magnets.

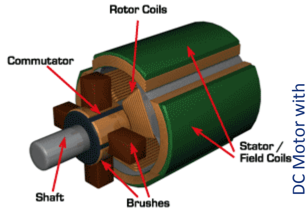
The commutator, the brushes and springs carry the electric current from outside the motor to the spinning wire windings of the rotor inside the motor. Due to friction between commutator and brushes, these elements must be regularly cleaned and/or replaced.

Advantages:
- low initial cost;
- high reliability;
- simple control of motor speed.

Disadvantages:
- high maintenance costs;
- low life-span for high intensity uses.



Permanent Magnet DC Motor



DC Motor with wound stator

Brushless DC motors

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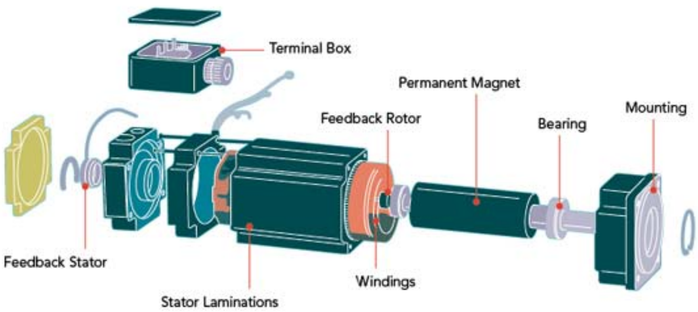
Typical brushless DC motors use a rotating permanent magnet in the rotor, and stationary electrical current/coil magnets on the motor housing for the rotor, but the symmetrical opposite is also possible.
A motor controller converts DC to AC.

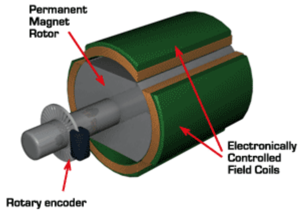


Brushless DC motors

This design is simpler than that of brushed motors because it eliminates the complication of transferring power from outside the motor to the spinning rotor.. Disadvantages include high initial cost, and more complicated motor speed controllers. Some such brushless motors are sometimes referred to as "synchronous motors" although they have no external power supply to be synchronized with, as would be the case with normal AC synchronous motors.

Advantages:
- long life span;
- little or no maintenance;
- high efficiency

Disadvantages:
- high initial cost (large permanent magnet required for the rotor and speed controller.);
- more complicated motor speed controllers

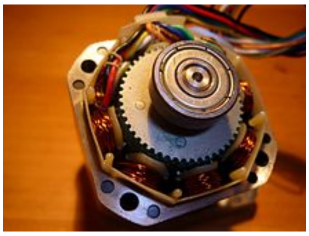


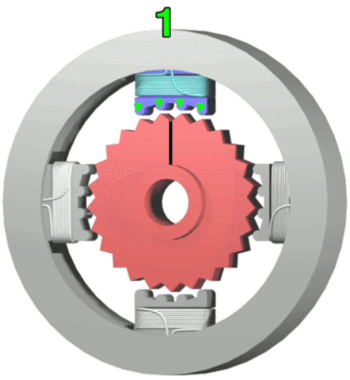
Brushless DC Motor ("in-runner" type)

Stepper motors

A stepper motor (or step motor) is a brushless DC electric motor that divides a full rotation into a number of equal steps. The motor's position can then be commanded to move and hold at one of these steps without any feedback sensor (an open-loop controller).

DC brush motors rotate continuously when voltage is applied to their terminals. Stepper motors, on the other hand, effectively have multiple "toothed" electromagnets arranged around a central gear-shaped piece of iron.



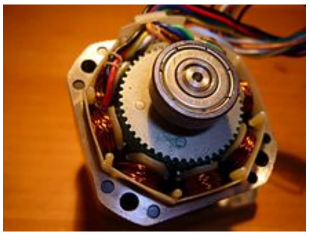


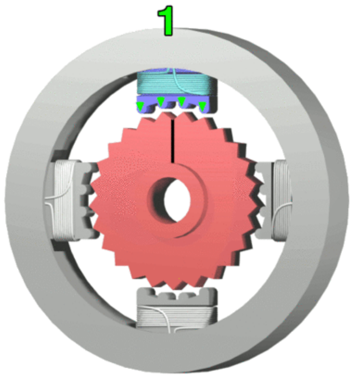
Stepper motors

The electromagnets are energized by an external control circuit. To make the motor shaft turn, first, one electromagnet is given power, which makes the gear's teeth magnetically attracted to the electromagnet's teeth.

When the gear's teeth are aligned to the first electromagnet, they are slightly offset from the next electromagnet. So when the next electromagnet is turned on and the first is turned off, the gear rotates slightly to align with the next one, and from there the process is repeated.

Each of those slight rotations is called a "step", with an integer number of steps making a full rotation. In that way, the motor can be turned by a precise angle.

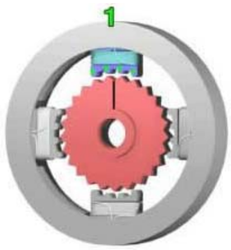




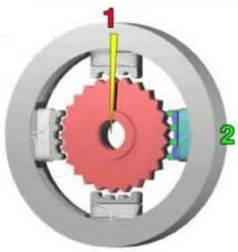
Stepper motors

How do they behave?

1. The top electromagnet (1) is turned on, attracting the nearest teeth of the gear-shaped iron rotor. With the teeth aligned to electromagnet 1, they will be slightly offset from right electromagnet (2).



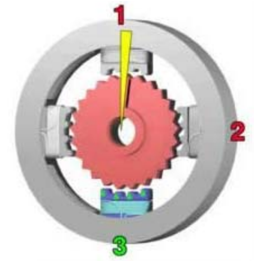
2. The top electromagnet (1) is turned off, and the right electromagnet (2) is energized, pulling the teeth into alignment with it. This results in a rotation of 3.6° in this example.



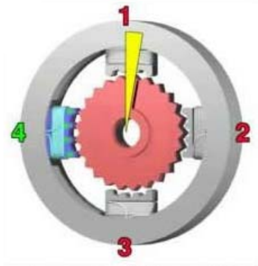
Stepper motors

How do they behave?

3. The bottom electromagnet (3) is energized; another 3.6° rotation occurs.



4. The left electromagnet (4) is energized, rotating again by 3.6°. When the top electromagnet (1) is again enabled, the rotor will have rotated by one tooth position; since there are 25 teeth, it will take 100 steps to make a full rotation in this example.



Stepper motor system

A Stepper Motor System consists of three basic elements, often combined with some type of user interface:

Indexers - The Indexer (or Controller) is a microprocessor capable of generating step pulses and direction signals for the driver. In addition, the indexer is typically required to perform many other sophisticated command functions.

Drivers - The Driver (or Amplifier) converts the indexer command signals into the power necessary to energize the motor windings. There are numerous types of drivers, with different voltage and current ratings and construction technology. Not all drivers are suitable to run all motors, so when designing a Motion Control System the driver selection process is critical.

Stepper Motors - The stepper motor is an electromagnetic device that converts digital pulses into mechanical shaft rotation. Advantages of step motors are low cost, high reliability, high torque at low speeds and a simple, rugged construction that operates in almost any environment. The main disadvantages in using a stepper motor is the resonance effect often exhibited at low speeds and decreasing torque with increasing speed.

AC motors

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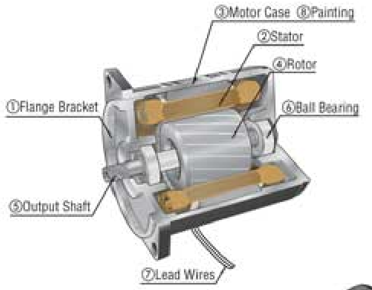
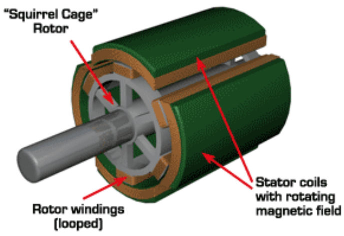
An AC motor is an electric motor driven by an alternating current (AC).

It commonly consists of two basic parts, an outside stationary stator having coils supplied with alternating current to produce a rotating magnetic field, and an inside rotor attached to the output shaft that is given a torque by the rotating field.





AC motors

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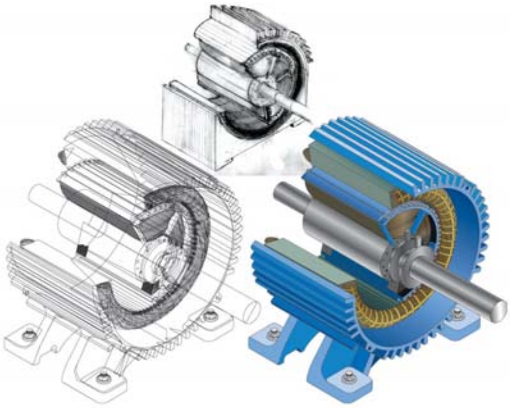
There are two main types of AC motors, depending on the type of rotor used.

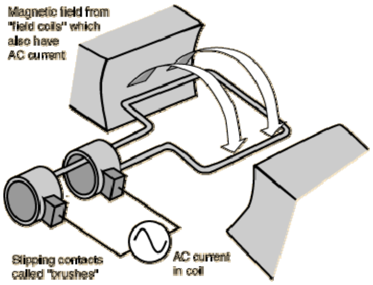
The first type is the **induction motor** or **asynchronous motor**. The magnetic field on the rotor of this motor is created by an induced current rather than being directly supplied to them.

An induction or asynchronous motor is an AC motor in which all electromagnetic energy is transferred by inductive coupling from a primary winding (stator) to a secondary winding (rotor), the two windings being separated by an air gap. In three-phase induction motors, that are inherently self-starting, energy transfer is usually from the stator to either a wound rotor or a short-circuited squirrel cage rotor. Three-phase cage rotor induction motors are widely used in industrial drives because they are rugged, reliable and economical.

AC motors

The second type is the **synchronous motor**. This type of motors rotates exactly at the supply frequency or a sub-multiple of the supply frequency. The magnetic field on the rotor is either generated by current delivered through slip rings or by a permanent magnet.





AC motors

How do they work

In both induction and synchronous motors, the AC power supplied to the motor's stator creates a magnetic field that rotates in time with the AC oscillations. Whereas the rotor of a synchronous motor turns at the same rate as the magnetic field of the stator, the rotor of an induction motor rotates at a slower speed than the stator field.

In an induction motor, the magnetic field of the stator is therefore changing or rotating relative to the rotor. This induces an opposing current in the rotor of induction motors, in effect the motor's secondary winding, when the latter is short-circuited or closed through an external impedance. The rotating magnetic flux induces currents in the windings of the rotor. These currents in turn create magnetic fields in the rotor that react against the stator field.

AC motors

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How do they work

Due to Lenz's Law, the direction of the magnetic field created will be such as to oppose the change in current through the windings. The cause of induced current in the rotor is the rotating stator magnetic field, so to oppose this the rotor will start to rotate in the direction of the rotating stator magnetic field. The rotor accelerates until the magnitude of induced rotor current and torque balances the applied load.

Since rotation at synchronous speed would result in no induced rotor current, an induction motor always operates slower than synchronous speed. The difference between actual and synchronous speed, also called **slip,** varies from about 0.5 to 5%.

AC motors

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How do they work

The induction machine's essential character is that it is created solely by induction instead of being separately excited as in synchronous or DC machines. For these currents to be induced, the speed of the physical rotor must be lower than that of the stator's rotating magnetic field, or the magnetic field would not be moving relative to the rotor conductors and no currents would be induced. As the speed of the rotor drops below synchronous speed, the rotation rate of the magnetic field in the rotor increases, inducing more current in the windings and creating more torque. The ratio between the rotation rate of the magnetic field as seen by the rotor (slip speed) and the rotation rate of the stator's rotating field is called slip.

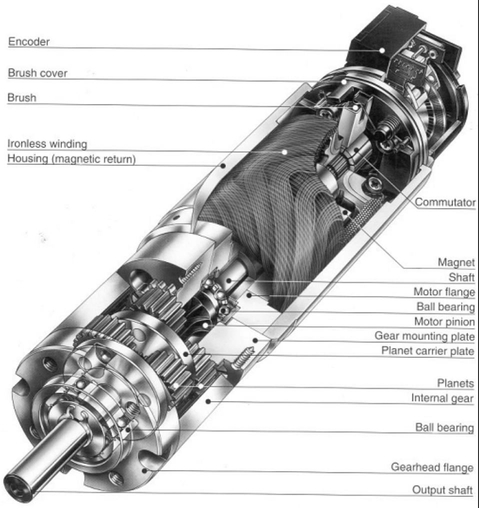
Under load, the speed drops and the slip increases enough to create sufficient torque to turn the load. For this reason, induction motors are sometimes referred to as asynchronous motors. An induction motor can be used as an induction generator, or it can be unrolled to form the linear induction motor which can directly generate linear motion.

Servomotors

A servomotor is a rotary actuator that allows for precise control of angular position.

It consists of a motor coupled to a sensor for position feedback, through a reduction gearbox. It also requires a relatively sophisticated controller, often a dedicated module designed specifically for use with servomotors.

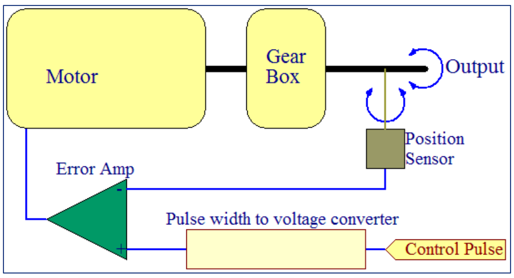
Servomotors are mainly used in applications such as robotics, CNC machinery or automated manufacturing.



Servomotors

As the name suggests, a servomotor is a servomechanism. More specifically, it is a closed-loop servomechanism that uses position feedback to control its motion and final position. The input to its control is some signal, either analogue or digital, representing the position commanded for the output shaft.

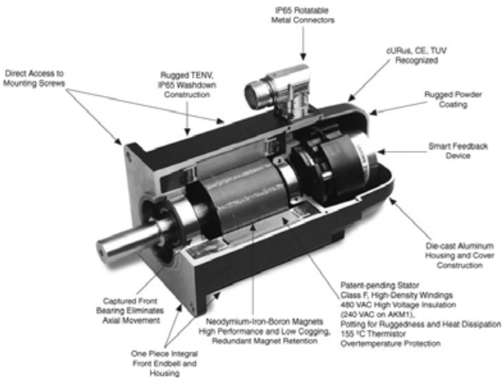
The motor is paired with some type of encoder to provide position and speed feedback. In the simplest case, only the position is measured. The measured position of the output is compared to the command position, the external input to the controller. If the output position differs from that required, an error signal is generated which then causes the motor to rotate in either direction, as needed to bring the output shaft to the appropriate position. As the positions approach, the error signal reduces to zero and the motor stops.



Servomotors

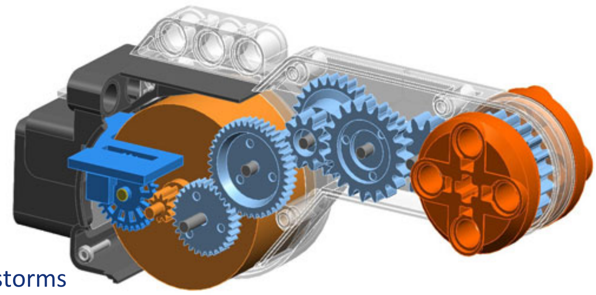
The very simplest servomotors use position-only sensing via a potentiometer and bang-bang (on-off) control of their motor; the motor always rotates at full speed (or is stopped). This type of servomotor is not widely used in industrial motion control, but they form the basis of the simple and cheap servos used for radio-controlled models.

More sophisticated servomotors measure both the position and also the speed of the output shaft. They may also control the speed of their motor, rather than always running at full speed. Both of these enhancements, usually in combination with a PID control algorithm, allow the servomotor to be brought to its commanded position more quickly and more precisely, with less overshooting.



Servomotors

The type of motor is not critical to a servomotor and different types may be used. At the simplest, brushed permanent magnet DC motors are used, owing to their simplicity and low cost. Small industrial servomotors are typically electronically-commutated brushless motors. For large industrial servomotors, AC induction motors are typically used, often with variable frequency drives to allow control of their speed. For ultimate performance in a compact package, brushless AC motors with permanent magnet fields are used, effectively large versions of Brushless DC electric motors.



NXT Mindstorms

Servomotors vs Stepper motors

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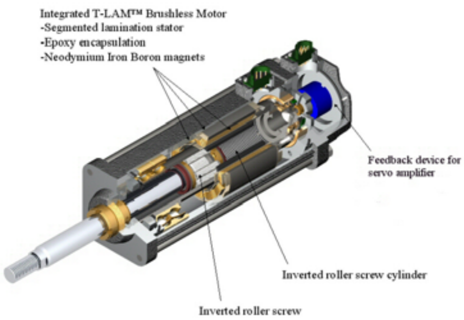
Servomotors are generally used as a high performance alternative to the stepper motor. Stepper motors have some inherent ability to control position, as they have built-in output steps. This often allows them to be used as an open-loop position control, without any feedback encoder, as their drive signal specifies the number of steps of movement to rotate. This lack of feedback though limits their performance, as the stepper motor can only drive a load that is well within its capacity, otherwise missed steps under load may lead to positioning errors.

The encoder and controller of a servomotor are an additional cost, but they optimise the performance of the overall system (for all of speed, power and accuracy) relative to the capacity of the basic motor. With larger systems, where a powerful motor represents an increasing proportion of the system cost, servomotors have the advantage.



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