Chapter 1: Introduction to Automation

Introduction

Industrial automation is the use of robotic devices to complete manufacturing tasks. In this day and age of computers, industrial automation is becoming increasingly important in the manufacturing process because computerized or robotic machines are capable of handling repetitive tasks quickly and efficiently. Machines used in industrial automation are also capable of completing tedious tasks that are not desirable to workers. In addition, the company can save money because it does not need to pay for expensive benefits for this specialized machinery. There are both pros and cons for a company when it comes to industrial automation.

Advantages and disadvantages

The main advantages of automation are:

- Replacing human operators in tedious tasks.
- Replacing humans in tasks that should be done in dangerous environments (i.e. fire, space, volcanoes, nuclear facilities, under the water, etc)
- Making tasks that are beyond the human capabilities such as handling too heavy loads, too large objects, too hot or too cold substances or the requirement to make things too fast or too slow.
- Economy improvement. Sometimes and some kinds of automation implies improves in economy of enterprises, by running 24 hours 365 days a year with non-stop.
- Accuracy and reliability can be achieved in every batch of products without human factors influence.

The main disadvantages of automation are:

- Technology limits. Current technology is unable to automate all the desired tasks.
- Unpredictable development costs. The research and development cost of automating a process is difficult to predict accurately beforehand.
- Initial costs are relatively high. The automation of a new product required a huge initial investment in comparison with the unit cost of the product, although the cost of automation is spread in many product batches.

Automation Pyramid (Levels of Automation)
Totally Integrated Automation-TIA is a strategy (Philosophies / architecture) in the automation technology. This strategy defines the interaction of extensive single components, tool and the services to achieve an Automation solution. The interaction performs integration across the automation levels of the automation pyramid. Based on the amount and number of the required components, the information to be transmitted within the different levels of a system can be portrayed in the form of a pyramid:

**Data transmission across and within the levels**

Bus systems (data transmission system in computerized architecture) provide the means for communication within the individual levels as well as between the different levels. That said, the following applies: the higher the level is, the slower the rate of transmission, but the greater the amount of data to be transmitted. PROFIBUS, CANopen, DeviceNet and AS-Interface Industrial Ethernet are known bus system protocols used within the level as well as for communicating to other levels.

*a. The sensor / actuator level (field level)*

This is the lowest of the levels, in this level sensors and actuators are used to control production and manufacturing processes.

Example for Process-related data:

- Liquid level
- Pressure
- Temperature
- Flow rate
This data is read-in and processed at the field level. In addition to the normal process data, safety- and quality-relevant data is also read-in, processed and transmitted. Amongst other, these include alarm values, run times, analysis values and so forth.

Data exchange takes place predominantly between different levels, and only seldom between the devices within the same level. For example, set-point values are transmitted from, and actual measured values are transmitted to a higher-level controller.

b. **The control or plant-floor level**

This control is positioned on the second level. Amongst others, the tasks covered by this level are:

- Conditioning and processing the data received from the assigned sensors and actuators on the field level.
- Administering several control and regulating modules
- Carrying out automation and control tasks
- Routing certain data to the system level
- Visual display of data

Typical devices for this level are, for example, programmable logic controllers (PLC) and regulators or CNC modules.

Data exchange takes place both between and within the levels. For example, set-point values are transmitted from a higher-level controller to the lower-level sensors and actuators.

This data can equally be transmitted between the individual PLC modules within this level.

c. **The control system or cell level**

This level is responsible for the monitoring, control and regulation of several processes. The tasks covered by this level are:

- Conditioning and processing the data received from the assigned controllers and regulators from the control level
- Administering several control and regulating modules
- Carrying out higher-level automation and control tasks

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- Routing certain data to the process control level
- Central point for visualization of selected data

Typical examples of such devices are: programmable logic controllers (PLC) and PCs.

Data exchange takes place both between and within the levels. For example, set-point values are transmitted from a higher-level management system to the lower level PLCs. This data can equally be transmitted between the individual PLC modules within this level.

d. The process control level and factory level

These two levels serve predominantly to control larger systems or factory operating areas as well as higher-level planning and control of the entire production.

These two levels are of less relevance as far as field-bus systems are concerned. On the process control level, Industrial Ethernet can be used for user-specific applications.

Basic Elements of Automation

An automated system consists of three basic elements:
1. **Power** to accomplish the process and operate the system,
2. A **program of instructions** to direct the process, and
3. A **control system** to actuate the instructions.

All systems that qualify as being automated include these three basic elements in one form or another.

Process v/s Discrete Manufacturing

The operational differences between process and discrete manufacturing are:

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<th>Process Manufacturing</th>
<th>Discrete Manufacturing</th>
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<th>Process industries mainly employ manufacturing operations that convert highly variable raw materials into consistent quality finished goods.</th>
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<td>Process manufacturers require a high degree of automation, monitoring, and advanced simulation and control for the more challenging operations.</td>
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<td>Emphasis is on continuous or batch mixing, reaction and separation of materials to produce other materials of higher value.</td>
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<tr>
<td>the benefits of automating the collection of real-time series data such as reducing waste, increasing flexibility and decreasing lead times</td>
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<td>Process manufacturers are using plant management applications in more advanced ways than companies in discrete industries</td>
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| Discrete manufacturers emphasize the assembly of high quality engineered components or sub-assemblies into more valuable final product configurations, or the physical manipulation of discrete entities. |
| Materials are often moved manually in discrete manufacturing environments, |
| Discrete companies are less automated and are prioritizing basic visibility into manufacturing, specifically into key performance indicators, finances, and data from production assets. |
| This ensures that they collect compliance data from manual processes providing a consistent high quality product. |

**Computer Process Control**

In computer process control, a digital computer is used to direct the operations of a manufacturing process. Although other automated systems are typically controlled by computer, the term computer process control is generally associated with continuous or semi-continuous production operations involving materials such as chemicals, petroleum, foods, and certain basic metals. In these operations the products are typically processed in gas, liquid, or powder form to facilitate flow of the material through the various steps of the production cycle. In addition, these products are usually mass-produced. Because of the ease of handling the product and the large volumes involved, a high level of automation has been accomplished in these industries.

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The modern computer process control system generally includes the following:

1. measurement of important process variables such as temperature, flow rate, and pressure,
2. execution of some optimizing strategy,
3. actuation of such devices as valves, switches, and furnaces that enable the process to implement the optimal strategy, and
4. Generation of reports to management indicating equipment status, production performance, and product quality.

Chapter 2: Sensors, Actuators & Other Control Systems

Sensor and Transducers

The term sensor is used for an element which produces a signal relating to a quantity measured. Thus in case of electrical resistance temperature element is used to measure the temperature in which sensor transfers the input temperature into a change in resistance, thus change in output voltage.

Term transducer is often used in place of sensor. Transducers are defined as the elements when subjected to a physical change will experience change in its property. Sometimes transducers are used to convert signals in one form to other.

Performance Terminology

Followings are some terms used to measure the performance of a sensor:

a. **Range:** this is the limit between which the input for a sensor can vary. For example a Load sensor for a measurement of force can have range 0kN to 50kN.
b. **Error:** this is the difference between the result of measurement and the true value of the quantity being measured. For example, a temperature sensor measures 25°C when actual temperature is 24°C, error in this case is +1°C, if actual temperature is 26°C then error is -1°C.
c. **Accuracy:** this is the extent to which the value indicated by the measurement system might be wrong. This is thus summation of all
the possible errors likely to occur, as well as the accuracy the sensor has been calibrated. For example, a temperature might be specified as ±2°C. This would mean that the reading given by the instrument can be expected to lie within + or -2°C.

d. **Sensitivity:** this is the relationship between the output measured per unit input, i.e. output/input. For example the sensitivity of a temperature sensor can be indicated as 0.5 Ω/°C.

e. **Hysteresis:** transducer or sensor can give different output for the same value of quantity measure while it is increasing and decreasing. This effect is called Hysteresis error.

f. **Repeatability:** this is the ability of the sensor to give the same output for various repeated applications of same input.

g. **Reproducibility:** this is the ability of a sensor to give same output when used to measure a constant input and is measure on a number of occasions.

h. **Stability:** this is the ability of a sensor to give the same output to measure a constant input over a period of time.

i. **Dead band:** this is the range of input values for which there is no output from the sensor, it is also called as dead space.

**Potentiometer**

A potentiometer consists of a resistance element with a sliding contact which can be moved over the length of the element, such element can be used for linear or rotary displacement measurement. Fig 2.5 illustrates a rotary potentiometer and its circuit diagram.

\[ V_s \] is the constant supply voltage between terminal 1 and 3, terminal 2 is free to displace on a resistance, thus the output voltage \( V_o \) depends on the position of terminal 2 on the resistance. There is a load resistance \( R_L \) connected across the output, where potential difference \( V_L \) is directly proportional to that of \( V_o \) for the infinite value of Load resistance. For finite value of load resistance, the effect of load resistance is to transfer what was a linear relationship between output voltage and angle into a non linear relationship.

**Strain Gauge Element**
The electrical resistance strain gauge is a metal wire (a), metal foil strip (b), or a strip of semiconductor material (c) which is wafer like and can be stuck onto surfaces like a postage stamp. When subjected to strain, its resistance value $R$ changes, the differential change in resistance $\Delta R/R$ being used as measurement of strain.

**Capacitive element**

The capacitance of a parallel plate capacitor is given by:

$$ C = \frac{\varepsilon_0 \varepsilon_r A}{d} $$

Where $\varepsilon_r$ is the relative permeability of the dielectric between the plates, $\varepsilon_0$ a constant called permeability of free space. $A$ is area of overlap between two plates and $d$ the distance between the plates separated.

Fig 2.7 show various types of capacitance sensors in which,

(a) one of the plate moves displacement ‘d’ thus causes change in capacitance
(b) one of the plate moves causing the overlap area ‘A’ between the plates causing the change in capacitance
(c) displacement of dielectric causes the change in relative permeability $\varepsilon_r$ thus affects capacitance
(d) often referred as push-pull sensor, which consists of two capacitor with a common plate in middle, which moves causing the distance ‘$d_1$’ and ‘$d_2$’ between capacitor 1 and 2 thus makes, when these two capacitor incorporated in a AC bridge, the bridge output voltage is proportional to the displacement.

**Differential transformer**
The linear variable differential transformer, generally called as LVDT consist of three coils systematically spaced along an isolated tube as in the figure 2.8. The central coil is the primary coil and the other two are secondary coils which are connected in series such a way that their outputs oppose each other. A magnetic core is moved through the central tube as a result of the displacement being measured.

When there is an alternating voltage input to the primary coil, an alternating e.m.f are induced in the secondary coils. With magnetic core element kept at center the magnetic field in each of secondary coil is the same, thus the e.m.f induced in each coil is the same. Since both are connected such that their output opposes each other, the net result is zero output.

However the central core is displaced ether in or out causes change in the magnetic field of one of the secondary coil to increase or decrease, which causes the e.m.f induced in one of the secondary coil is greater than other, thus net result is now a non zero output, depending on how much the magnetic field of the coil. Thus displacement of the central core causes the proportional net output.

**Optical encoder (sensor)**

Encoder is a device that provides a digital output as a result of linear or angular displacement. Fig 2.10 shows a basic optical encoder in which a light bean passes through slots in discs that is detected by a suitable light sensor. Out of two discs one is fixed and other is rotating, the rotating disc has series if slots at designated angular position. When this disc rotates, the light sensor generates pulsed output based on the angular position of the disc. Thus form angular position to the rotation of the shaft can be determined taking the reference of a datum slot. Fig 2.12 shows how optical encoder can be used to detect the linear displacement.
Pneumatic sensor

Pneumatic sensor can be used to measure the displacement. It involves use of compressed air at constant pressure ‘$P_s$’ above atmospheric pressure. This air is allowed to flow through the orifice and escape through the nozzle into atmosphere. The pressure ‘$P$’ between orifice and nozzle is measured. The escape of air through nozzle is controlled by the displacement of a flapper. When the flapper is closest to the nozzle i.e. $x=0$ then no air escapes and pressure $P$ equal to the supply pressure $P_s$. As ‘$x$’ increases the measured $P$ goes on decreases proportional to the displacement ‘$x$’.

Strain gauge Load cell

Strain gauge load cell is a very commonly used form of force measuring transducer. It is based on the use of electrical resistance strain gauges to monitor the strain produced in some member when stretched, compressed or bent by the application of force. The arrangement generally referred as ‘Load Cell’ as shown in the Fig 2.15. It consists of a cylindrical tube to which strain gauges have been attached. When force is applied to the cylinder to compress it, then the strain give resistance change which is the measurement of strain and hence the applied force. Such load cell is typically used measure up to 10MN.

Mechanical type of Fluid Pressure transducers

There are many type of devices used to monitor fluid pressure in industrial processes like, diaphragm, capsules, bellows and tubes.
For diaphragm the difference in the pressure on either side of it can displace and this can be monitored by direct analogue meters or by strain gauges as in Fig 2.16 (a) and (b).

Capsules type Fig 2.16 (c) is made of two diaphragms which can give better sensitivity than a single diaphragm device, to improve the further sensitivity number of capsules can be increased as in Fig 2.16 (d).

Bourdon introduced a C-shape tube with elliptical cross section which can sense the pressure and deflect as in Fig 2.16 (e), same tube can be used in helical form for higher sensitivity.

**Fig. 2.16 Various mechanical types of fluid pressure monitoring devices**

**LVDT-Bellow type pressure transducer**

The linear variable differential transformer, generally called as LVDT consist of three coils systematically spaced along an isolated tube as in the figure 2.8. The central coil is the primary coil and the other two are secondary coils which are connected in series such a way that their outputs oppose each other. A magnetic core is moved through the central tube as a result of the displacement being measured.

When there is an alternating voltage input to the primary coil, an alternating e.m.f are induced in the secondary coils. With magnetic core element kept at center the magnetic field in each of secondary coil is the same, thus the e.m.f induced in each coil is the same. Since both are connected such that their output opposes each other, the net result is zero output.

However the central core is displaced ether in or out causes change in the magnetic field of one of the secondary coil to increase or decrease, which causes the e.m.f induced in one of the secondary coil is greater than other, thus net result is now a non zero output, depending on how much the magnetic field of the coil. Thus displacement of the central core causes the proportional net output. If a bellow is attached to the central plunger of LVDT which can actuate due to change is pressure, the LVDT output can be used as pressure measurement.

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**Turbine meter**

Turbine flow meter consists of a multi-bladed rotor that is supported centrally in the pipe along which the flow occurs. The fluid flow results in rotation of the rotor, the angular velocity being approximately proportional to the flow rate.

The rate of revolution of the rotor can be determined using magnetic pick-up which produces induced e.m.f. pulse every time a rotor blade passes it as the blades are made of magnetic material or small magnet mounted on the tip. The pulses are counted and so the number of revolutions of the rotor can be determined.

**Fluid Level Sensor - Float**

A direct method of monitoring the level of liquid in a vessel is by monitoring the movement of the float. Figure shown illustrates a simple float system. The displacement of the float causes a lever arm to rotate and so moves a slider across the potentiometer. The result is an output of voltage related to the height of liquid.

**Differential pressure Fluid level sensor**

Figure below shows two types of level measurement based on the differential pressure. In figure (a) the differential pressure cell determines the pressure difference between the liquid at the base of the vessel and atmospheric pressure. With closed vessel the system showed in figure (b) can be used. The differential pressure cell monitors difference in pressure between the base of the vessel and the air/gas above the surface of the liquid.
**Bimetal Strip**

This device consists of two different metal strips bonded together. The metals have different coefficient of expansion and when the temperature changes the composite strip bends in to curved strip, with the higher coefficient metal on the outside the curve. This deformation may be used as a temperature controlled switch as in the figure.

**Thermistors**

Thermistors are small piece of material made from mixtures of metal oxides, such as those of chromium, cobalt iron, manganese and nickel. These oxides are semiconductors. The material is formed into various forms like beads, discs and rods as in figure. The change in resistance per degree change in temperature is considerably larger than that occurs in metal. This change in resistance can be used to vary the voltage output as temperature signal.

**Thermocouple**

If two different metals are joined together and each of junctions is with temperature difference, then a potential difference occurs across the junction. If both junctions are at same temperature there is no net e.m.f. if however there is a difference in temperature between the two junctions there is an e.m.f. which depends on the metals used and the temperature difference. Usually one end
is held at 0°C and then other with measuring temperature for better accuracy.

**Read Switch**

Figure shows a basic form of read switch. It consists of two magnetic contacts sealed in a glass tube. When magnet is brought close to switch, the magnetic reeds are attracted to each other and close the switch contacts. This is non contact proximity switch, these switches are used in door operation counts and also in speed sensitive tachometer.

**Selection of Sensor**

In selecting sensor for a particular application there are a number of factors that need to be considered.

a. Identify the nature of measurement required i.e. the variable to be measured, its nominal value, the accuracy required, environmental conditions under which measurements to be made.

b. Identify the nature of output required from the sensor, this determining the signal conditioning requirements in order to give suitable output signals from the measurement.

c. Identify the possible sensor, taking in to account the factors their range, accuracy, speed of response, reliability life, power supply requirements, availability and cost.
Chapter 3: Pneumatic and Hydraulic Actuation systems

**Actuators:** these are the elements of control system which are responsible for transforming the output of microprocessor or control system into a control action on a machine or device. For example an electrical output from the controller has to be transformed into a linear motion to move a load or to control the flow of liquid passing along pipe.

**Pneumatic Actuators:** Pneumatic signals are often used to control the final control element even when the control system is to operate large valves or other high power control devices. The main drawback of this system is the compressibility of air. Generally signals controlled by pneumatic controls devices are in the region of 20 to 100kPa gauge pressure.

Current to pressure convertor: This system is used to convert the current output of say 4 to 20mA from controller to a pneumatic pressure signal of 20 to 100kPa to operate the actuator. Input current passes though coils mounted on a core which is then attracted towards a magnet. Extent of attraction depends of the size of current. Movement of the core causes movement of the lever about its pivot and so the movement of a flapper above the nozzle. The position of the flapper in relation to the nozzle determines the size of the air pressure in the system. Refer to the figure below that illustrates the system.
Hydraulic Actuators: Usually hydraulic actuating systems are used to operate the control devices, whose range is above the pneumatic actuators, i.e. the pressure above 100kPa. However the drawback of hydraulic systems is that they are much more expensive than pneumatic devices and there are hazard associated with oil leakage which can cause pressure drop in the system or lack of oil and the oil can spill over other components of the system causing damage to the component.

Pneumatic power supply system

A pressurized air is required which is supplied by an air compressor which is driven by electrical motor. Air inlet to the compressor is likely to be filtered to avoid the dust and foreign elements by entering the system. A silencer is also fitted in between to avoid the excessive noise. A pressure relief valve is being used to provide the protection against the pressure in the system rising above safe level.
Since air compressor increases the temperature of the air, a cooler is likely to follow and a moisture remover to remove moisture from the air which can cause rust in the system parts. A storage cylinder is used to perform the same action as accumulator in hydraulic system to smoothen out any short-term pressure fluctuations.

**Hydraulic power supply system**

For this system a source of pressurized oil is required, which is provided by a pump driven by an electrical motor. The pump pumps the oil from the sump through a non-return valve and an accumulator to the system, from which it returns to the sump as shown in the figure above. A pressure relief valve is included to release the pressure if it exceeds the safety levels. The non-return valve is to prevent the oil being back driven to the pump. Accumulator is to smooth out any short-term fluctuations in the output oil pressure; it is just a container in which oil is held with pressure against to an external force using piston as show in figure. If pressure increases in the system then the piston rises up to increase the volume. If the pressure drops in the system then the piston drops down to reduce the volume there by increasing the pressure.

**Control valves:** Both pneumatic and hydraulic systems use control valves to direct and regulate the flow of fluid through a system. Valves can be considered to be either infinite position or finite position valves. **Infinite position valve** can make up any position between the fully opened to fully closed positions. **Finite position valves** are either completely open or completely closed; they are ON/OFF devices. The connections to the valves are through ports.

4 port control valve: The figure below illustrate the 4 port valve the load (final control device) is connected to the port A and B, the pressure supply from the pump or compressor is to port P and in the case of hydraulic valve the fluid is returned to sump through port T. In case of pneumatic the return would be vented to atmosphere. Figure bellow shows 4 port valve connection and also 4/2 and 4/3 configurations.
4 port valve connection (a) Extend P-B and A-T (b) Retract P-A and B-T

Valve Symbols

4 port valve can have three configuration which are represented as below

a. 4/2 configuration
b. 4/3 with P and T connected in off position
c. 4/3 with A, B and T connected in off position
Valve control methods

Following Fig 5.7 shows symbols to represent various valve control methods which are used in hydraulic and pneumatic circuit design.

(a) 4 port valve with push button control with a return spring
(b) 4 port valve with solenoid control with a return spring

Fig. 5.7 Control methods

Pneumatic Lift System

Figure shows a simple example of an application of valves in a pneumatic lift system. Two push button 2/2 valves are used. When the button on the up level is
pressed, the load is lifted. When the button on the down valve is pressed the load is lowered. Note that with pneumatic system an open arrow is used to indicate a vent to the atmosphere.

**2/2 poppet valve and**

The figure below illustrates the basic form of a 2/2 poppet valve which is normally closed condition. In poppet valve, balls, discs or cones are used in conjunction with valve seats to control the flow. In the figure a ball is shown as example. When push button is depressed the ball is pushed out of its seat and flow occurs. When the button is released, the spring forces the ball back up against its seat and so closes off the flow.

![Image of a 2/2 poppet valve](image)

**Spool or 4/2 shuttle valve**

In a spool valve a spool moves horizontally within the valve body to control the flow. Figure below show the 4/2 form of spool valve. As shown B is connected to P with A and T closed. When spool is moved to the left, A is connected to P with B and T closed. Spool might be moved using push button, liver or solenoid. Rotary spool valve have a rotating spool switch, when it rotates, opens and closes the port in similar way.

![Image of a spool valve](image)

**Pilot operated system**

The force required to move the ball or shuttle in a valve can often be too large for manual or solenoid operation. To overcome this problem a “pilot-operated system” is used where one valve is used to control the second valve. Following figure illustrates this. Pilot valve is small capacity and can be operated with manual or solenoid. There by pilot valve allows the system pressure to control the main valve. The pilot port on the main valve is denoted by Z, Y,X and the pilot pressure line is denoted by dashed line. Pilot system can be operated using separate valves, but in some cases both are combined in single housing.

![Image of a pilot operated system](image)

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Directional valve

The diagram below shows a simple directional valve and its symbol. Free flow can only occur in one direction through the valve, when the ball is pressed against the spring. Flow in the other direction is blocked by the spring forcing the ball against its seat.

Pressure relief valve
Sequential system

Hydraulic and Pneumatic Cylinders
Rotary actuators

![Diagram of a rotary actuator](image)

Fig. 5.17 Rotary actuators: (a) vane rotary, (b) hydraulic motor

Diaphragm actuator
Valve bodies

Plug shapes and characters
Chapter 6: Basic System Models

Mathematical Model

In order to understand the behavior of a system, mathematical models are needed. These are the equations which describe the relationship between the input and output of a system. They are used to forecast the behavior of the model under specific conditions. These mathematical models are based on fundamental physical laws that govern the behavior of the system.

Mechanical system building blocks

The models used to represent the mechanical system have the basic building blocks of springs, dashpots and masses. Springs represent the stiffness of a system, dashpot represents the force opposing the motion i.e. frictional or damping effects and masses are the inertia or resistance to acceleration. A mechanical model does not have to be made by springs, dashpot or masses, but have the property of stiffness, damping and inertia. All these building blocks can be considered to have a force as an input and displacement as output.

In case of spring building block, the stiffness of a spring is described by the relationship between force ‘F’ used to extend or compress a spring and the resulting extension or compression ‘x’.

\[ F = k \cdot x \]

Where ‘k’ is a constant called as spring stiffness, bigger the value of ‘k’ greater the forcec have to be to stretch or compress. Energy stored by spring is given by

\[ E = \frac{1}{2} \frac{F^2}{k} \]

Dashpot building block represents the type of forceers experienced when we attempt to push an object through a fluid or to move against to a frictional force. Faster the object is pushed greater becomes the opposing force. The dashpot which is used
pictorially to represent these damping forces which slow down moving objects consists of a piston moving in a closed cylinder as in figure.

Movement of the piston requires the fluid on one side of the piston to flow through the piston. This produces a resistive force. This resistive force ‘F’ is oppositional to the velocity ‘v’ of the piston. Thus

\[ F = c \cdot v \]

Where ‘c’ is constant called as damping coefficient. Larger the value of ‘c’ the grater the damping force at a particular velocity. Since velocity is the rate of change of displacement ‘x’ of the piston, i.e.

\[ F = c \cdot \frac{dx}{dt} \]

Thus relationship between the displacement ‘x’ of the piston i.e. output and the forcer as the input is a relationship depending on the rate of change of the output. The power dissipated by the dashpot is give by

\[ P = cv^2 \]

The **mass building block** exhibits the property that the bigger the mass greater the mass required to give it a specific acceleration. The relation between the force and the acceleration is (Newton’s second law) \( F = m \cdot a \), where the constant of proportionality between the force and the acceleration is the constant called ‘m’. Acceleration is the rate of change of velocity i.e. \( \frac{dv}{dt} \) and velocity is rate of change of displacement i.e. \( \frac{dx}{dt} \). Thus,

\[ F = ma = m \frac{dv}{dt} = m \frac{d(dx / dt)}{dt} = m \frac{d^2x}{dt^2} \]

Energy stored by the mass system is give by the formula

\[ E = \frac{1}{2} mv^2 \]

**Rotational Systems**
The spring, dashpot and mass are the three basic building block of mechanical system, where force and linear displacement are involved without any rotation. If there is rotation then the equivalent three building blocks are a torsional spring, a rotary damper and moment of inertia or inertia of rotating mass. With these building blocks the input is torque and output is rotational displacement.

For torsional spring torque $T$ is proportional to the angular displacement $\theta$ with a constant ‘$k$’ called spring stiffness, thus

$$T = k\theta.$$  

With rotary damper torque $T$ is proportional to the angular velocity $\omega$ and since angular velocity is rate of change of angular displacement i.e. $d\theta/dt$, thus

$$T = c\omega = c \frac{d\theta}{dt}.$$  

The moment of inertia building block exhibits the property that the greater the moment of inertial $I$ greater the torque need to produce an angular acceleration $\alpha$, thus

$$T = I\alpha = m \frac{d\omega}{dt} = I \frac{d(d\theta/dt)}{dt} = I \frac{d^2\theta}{dt^2}.$$  

Refer to the following table for the mathematical model for mechanical building blocks
Building up a mechanical system

Many systems can be considered to be essentially mass, dashpot and spring combined in a way as shown in the fig 8.4. To evaluate the relation between the force and displacement for the system just consider the mass and forces acting on the mass. It is as shown in Free Body Diagram.
Industrial Automation and Control Systems

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Electrical Building Blocks

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The basic building blocks of electrical system are inductor, capacitor and resistors. For an inductor the potential difference ‘v’ across it at any instant depends on the rate of change of current through it.

\[ v = L \frac{di}{dt} \]

Where ‘L’ is inductance. The direction of the potential difference is in the opposition direction to the potential difference used to drive the current through the inductor. Hence the term back e.m.f. The equation can be rearranged to give

\[ i = \frac{1}{L} \int v \, dt \]

For a capacitor the potential difference across it depends on the change of ‘q’ on the capacitor plates at the instant concerned.

\[ v = \frac{q}{C} \]

Where C is the capacitance. Since the current ‘i’ to or from the capacitor is the rate at which charge moves to or from the capacitor plates, i.e.

\[ i = \frac{dq}{dt} \]

Then the total charge ‘q’ on the plates is given by

\[ q = \int i \, dt \quad \text{and so} \quad v = \frac{1}{C} \int i \, dt \]

Alternatively, since \( v = \frac{q}{C} \) then

\[ \frac{dv}{dt} = \frac{1}{C} \frac{dq}{dt} = \frac{1}{C} i \]

\[ i = C \frac{dv}{dt} \]
For resistor, the potential difference ‘v’ across it at any instant depends on the current ‘i’ through it.

\[ v = Ri \]

Where R is the resistance

Both the inductor and capacitor store energy which can then be released at a later time. A resistor does not store energy but just dissipate it. The energy stored by an inductor when there is a current ‘i’ is

\[ E = \frac{1}{2} Li^2 \]

The energy stored by a capacitor when there is a potential difference ‘v’ across it is

\[ E = \frac{1}{2} Cv^2 \]

The power dissipated by a resistor when there is a potential difference ‘v’ across it is

\[ P = iv = \frac{v^2}{R} \]

Table below summarizes the equations defining the characteristics of the electrical building blocks when the input is current and the output is potential difference.

<table>
<thead>
<tr>
<th>Building block</th>
<th>Describing equation</th>
<th>Energy stored or power dissipated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductor</td>
<td>( i = \frac{1}{L} \int v , dt )</td>
<td>( E = \frac{1}{2} Li^2 )</td>
</tr>
<tr>
<td>Capacitor</td>
<td>( i = C \frac{dv}{dt} )</td>
<td>( E = \frac{1}{2} Cv^2 )</td>
</tr>
<tr>
<td>Resistor</td>
<td>( i = \frac{v}{R} )</td>
<td>( P = \frac{v^2}{R} )</td>
</tr>
</tbody>
</table>